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GLOBAL UNCERTAINTY ANALYSIS OF FULL-SCALE SUBMARINE PROPULSION PREDICTIONS USING TOW-TANK MODEL TESTS

by
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Estimates of the uncertainties attached to full-scale predictions of submarine resistance and propulsion based on standard submarine tow-tank model tests are obtained by means of a global uncertainty analysis. The analysis takes into account all the component uncertainties, including the uncertainties associated with the prediction procedure and the measurements performed both at model scale and at full scale, which influence the overall uncertainty of full-scale predictions.

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CONTENTS

ABSTRACT

Estimates of the uncertainties attached to full-scale predictions of submarine resistance and propulsion based on standard submarine tow-tank model tests are obtained by means of a global uncertainty analysis. The analysis takes into account all the component uncertainties, including the uncertainties associated with the prediction procedure and the measurements performed both at model scale and at full scale, which influence the overall uncertainty of full-scale predictions.

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INTRODUCTION

Estimates of the uncertainties attached to full-scale predictions of submarine resistance and propulsion based on standard submarine tow-tank model tests are obtained in this study by means of a global uncertainty analysis. The analysis takes into account the uncertainties associated with the prediction procedure and the uncertainties of measurements performed both at model scale and at full scale. Thus, the uncertainty analysis developed in the study takes into account all the component uncertainties which influence the overall uncertainty of full-scale predictions.

The prediction procedure, summarized in Appendix A, entails both resistance and propulsion tests. Five primary model-scale variables are measured in these model-scale tests. These measured primary model-scale variables are the carriage speed and the drag, which are measured in both resistance and propulsion tests, and the propeller rpm, thrust, and torque measured in propulsion tests.

The five measured primary model-scale variables are used to determine several "transformed" model-scale variables via analytical relations. These relations are given in Appendix A. The transformed model-scale variables include the residuary-drag coefficient, determined in resistance tests, and four nondimensional variables obtained via propulsion tests : the total-drag coefficient, the advance ratio, the thrust-deduction factor, and the propulsive efficiency.

The curves representing the advance ratio, the thrust-deduction factor, and the propulsive efficiency as functions of the total-drag coefficient are fundamental elements of the model-scale to full-scale extrapolation. The relations used in this extrapolation are given in Appendix A. The extrapolation procedure is usually implemented for a specified full-scale speed or for a specified full-scale shaft horsepower. Both cases are examined in the global uncertainty analysis developed in the study. Three other cases, in which full-scale predictions are obtained for a specified value of the propeller rpm, thrust, or torque, are also examined for completeness.

The uncertainty analysis, based on classical expressions for the errors [1] and elementary differential calculus, is expounded in Appendix B. The Fortran-code implementation of the expressions for the uncertainties obtained in Appendix B is given in Appendix C. Example input and output files associated with the Fortran-code are also included in Appendix C. The global uncertainty analysis developed in Appendices B and C provides a practical tool for estimating the uncertainties of full-scale predictions in terms of component uncertainties attached to model-scale and full-scale measurements.

Full-scale theoretical predictions are ultimately compared to values measured in full-scale trials. The observed differences between the full-scale measurements and the full-scale values predicted using model-scale tests are usually expressed in the form of a correlation allowance in the relation defining the drag coefficient.

The correlation allowance accounts for aspects of the full-scale flow, such as the hull roughness, that cannot be accounted for in model tests. The correlation allowance also accounts for other limitations of the model-test to full-scale prediction procedure, notably errors that are systematically introduced into the predictions due to limitations inherent to the prediction procedure. Thus, systematic errors associated with the characteristics of the tow-tank and the experimental set-up used in the implementation of the prediction procedure are largely included in the correlation allowance, as is attested by the fact that different correlation allowances are used for different tow-tanks.

Thus, the correlation allowance largely accounts for the systematic (bias) errors associated with the effects of the tank bottom and walls, the influence of the strut holding the model, the strain gauges, and the electronic equipment. Therefore, as long as no significant changes are made in the characteristics of the tow-tank, the strut, the strain gauges, the electronic equipment, and the testing procedure, systematic errors attached to these aspects of the prediction procedure can largely be ignored in the uncertainty analysis (since they are already included in the correlation allowance to a large extent, as was noted previously).

Errors stemming from residual waves in the tank and differences between full-scale and model-scale depth of submergence can also be ignored in the uncertainty analysis to a large extent, although these errors are likely to vary with the design speed, and thus cannot be completely ignored in the uncertainty analysis. Additional systematic errors due to geometrical imprecisions of the model clearly are model-dependent, and thus cannot in principle be ignored in the uncertainty analysis.

In summary, it is proper to ignore most systematic (bias) errors in an uncertainty analysis of a consistent prediction procedure because these consistent errors are largely included in the correlation allowance attached to the prediction procedure. This general consideration and consideration of the substantial difficulties involved in obtaining reliable estimates of bias errors --- more precisely, of the effects of the bias errors that are not already included in the correlation allowance --- suggest that a reasonable practical way of accounting for bias errors is to simply increase the precision (random) errors by means of a multiplicative factor. Specifically, the bias errors of the measured primary model-scale variables are taken equal to the precision errors of these variables in the analysis considered further on. This practical approach is justified by the extreme complexities, and uncertainties, involved in obtaining realistic estimates of the influence of the bias errors that are not already included in the correlation allowance upon full-scale prediction uncertainties.

The precision errors attached to the measured primary model-scale variables are determined via a statistical analysis of the repeatability of model-scale measurements. This repeatability analysis is presented in Appendix D.

Results of the repeatability analysis presented in Appendix D and of the global uncertainty analysis expounded in Appendix B are presented below for several cases, with the purpose of analyzing the contribution of the major component uncertainties which influence the overall uncertainty of full-scale predictions.

RESULTS OF UNCERTAINTY ANALYSIS

The uncertainty analysis developed in the study is applied to a typical case, which is defined below (and in the input file listed in Appendix C). The identifying numbers of the model, the propeller, and the resistance (EHP) and propulsion (SHP) tests corresponding to the case considered here are

model no.	propeller no.	EHP exp. no.	SHP exp. no.
XXXX	XXXX	XXX	XXX

The tank-water density and viscosity are

density	viscosity
1.937 $slug/ft^3$	$1.084X10^{-5}$ ft^2/sec

The length and the wetted-surface area of the model, and the diameter of the propeller are

length	area	prop diameter
22.697 ft	138.179 ft^2	0.9986 ft

The carriage speed and the drag in the resistance (EHP) tests are

speed	drag
6.0 knots	46.66 lbs

The carriage speed, the propeller rpm, the total drag R_T, the tow force ΔR, and the propeller thrust and torque in the propulsion tests are

speed	rpm	drag	tow force	thrust	torque
18.0 knots	923.4	392.64 lbs	70.1 lbs	551.0 lbs	1501.0 in-lbs

The slopes of the curves representing the advance ratio, the thrust-deduction factor, and the propulsive efficiency as functions of the total-drag coefficient are respectively equal to

advance ratio	thrust-deduction factor	propulsive efficiency
-0.249	0.067	-0.015

The length and the speed of the full-scale submarine are taken as

length	speed
380 ft	25 knots

Finally, the viscosity of sea-water is assumed equal to $1.282\text{X}10^{-5}$ ft^2/sec.

As was already noted, results of the repeatability analysis presented in Appendix D and of the global uncertainty analysis expounded in Appendices B and C are presented for several cases for the purpose of analyzing the contribution of the major component uncertainties which influence the overall uncertainty of full-scale predictions.

Case M1 : contribution of precision uncertainties of model-scale measurements

It is instructive to begin by considering the full-scale prediction-uncertainties for the case when only the uncertainties that directly stem from model tests are taken into account. In this case, called M1 hereafter, the correlation allowance and full-scale conditions (i.e. the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, the full-scale values of the speed, the propeller rpm, the thrust, the torque, and the shaft horsepower) are presumed known without uncertainty. The density and the viscosity of tank water, the length and the wetted-surface area of the model, and the propeller diameter are also presumed known without uncertainty in case M1. Furthermore, model-scale uncertainties are taken equal to the precision (random) errors determined in Appendix D. Thus, bias errors attached to the measured primary model-scale variables are not taken into account in case M1. Case M1 corresponds to a comparison of successive model tests within a series of consecutive tests.

The analysis of the repeatability of measurements of the five primary model-scale variables for standard submarine model testing given in Appendix D shows that relative precision uncertainties in resistance (EHP) tests are approximately equal to 0.15% for the carriage speed and 1.2% for the drag. These uncertainties are indicated in the following table :

Precision uncertainties of model-scale measurements in EHP tests

speed	drag
0.15%	1.2%

Appendix D indicates that the relative precision uncertainties in propulsion (SHP) tests are approximately equal to 0.15% for the carriage speed, 0.3% for the propeller rpm, 1.2% for the drag R_T and the tow force ΔR , and 0.5% for both the propeller thrust and torque. These uncertainties are listed below :

Precision uncertainties of model-scale measurements in SHP tests

speed	rpm	drag	tow force	thrust	torque
0.15%	0.3%	1.2%	1.2%	0.5%	0.5%

The analysis and the Fortran-code given in Appendices B and C show that the model-scale measurement uncertainties defined above yield a relative uncertainty of the residuary-resistance coefficient C_R approximately equal to 6% . The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the previously-defined model-scale uncertainties are listed in the next table for five cases, corresponding to rows number 2 to 6 of the table. These five cases correspond to predictions for a specified value of the full-scale speed, rpm, thrust, torque, or SHP.

Full-scale prediction-uncertainties for case M1

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	0.35%	2.2%	2.25%	2.2%	1.55%
rpm	0.35%	n/a	2.3%	2.4%	2.4%	1.8%
thrust	1.15%	1.2%	n/a	2.25%	2.95%	2.5%
torque	1.15%	1.25%	2.25%	n/a	1.25%	0.95%
SHP	0.75%	0.85%	1.95%	0.85%	n/a	1.6%

The prediction-uncertainties given in the second and third rows, which respectively correspond to predictions for given full-scale values of the speed or the rpm, of the foregoing table are nearly identical. The prediction-uncertainties given in the bottom row of the table, corresponding to predictions for a given full-scale value of the shaft horsepower, are on the whole somewhat smaller than the prediction-uncertainties listed in the other rows.

The prediction-uncertainties listed in the foregoing table represent the contribution of precision errors of model-scale measurements when all other sources of errors (including bias errors of model-scale measurements, uncertainties of the density and the viscosity of tank water, and model-scale geometrical inaccuracies) are ignored. As was already noted, this table of prediction-uncertainties corresponds to a comparison of successive model tests within a series of consecutive tests. The contribution of uncertainties of the density and the viscosity of tank water, the model length and wetted-surface area, and the propeller diameter, are considered in case M2; and the sensitivity of prediction-uncertainties to model-scale bias errors is considered in case M3.

Case M2 : contribution of uncertainties of tank-water properties and model-scale geometry

The uncertainties of the density and the viscosity of tank water, the model length and wetted-surface area, and the propeller diameter are taken as is indicated below.

Uncertainties of tank-water properties and model-scale geometry

density	viscosity	length	area	prop diameter
0.1%	1.5%	0.1%	0.5%	0.05%

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the uncertainties of model-scale measurements defined in case M1 and the uncertainties of tank-water properties and model-scale geometry now considered are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque, or SHP , as for case M1.

Full-scale prediction-uncertainties for case M2

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	0.35%	2.3%	2.35%	2.3%	1.65%
rpm	0.35%	n/a	2.4%	2.5%	2.5%	1.95%
thrust	1.2%	1.25%	n/a	2.25%	3.0%	2.55%
torque	1.2%	1.3%	2.25%	n/a	1.3%	1.0%
SHP	0.8%	0.85%	1.95%	0.85%	n/a	1.6%

These uncertainties are not significantly larger than those obtained for case M1. Thus, the uncertainties of the density and the viscosity of tank water, of the length and the wetted-surface area of the model, and of the diameter of the propeller are sufficiently small that they have insignificant effect upon the prediction-uncertainties.

Case M3 : contribution of model-scale precision and bias uncertainties

As in cases M1 and M2, only the contribution of model-scale uncertainties are considered in case M3. Thus, the correlation allowance and full-scale conditions (i.e. the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, the full-scale values of the speed, the propeller rpm, the thrust, the torque, and the shaft horsepower) are again presumed known without uncertainty for the case M3 now considered.

As was already noted in the introduction, model-scale bias errors are taken equal to the model-scale precision errors determined in Appendix D and listed previously for cases M1 and M2. The total (precision + bias) model-scale uncertainties which are considered in case M3 are then equal to $2^{1/2}$ times the uncertainties considered in cases M1 and M2.

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the previously-defined model-scale uncertainties are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP , as for cases M1 and M2. This table indicates that the prediction-uncertainties for case M3 are equal to $2^{1/2}$ times the prediction-uncertainties for case M2, as one expects.

Full-scale prediction-uncertainties for case M3

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	0.45%	3.25%	3.3%	3.3%	2.35%
rpm	0.45%	n/a	3.35%	3.55%	3.55%	2.75%
thrust	1.7%	1.75%	n/a	3.2%	4.25%	3.6%
torque	1.7%	1.85%	3.2%	n/a	1.85%	1.4%
SHP	1.1%	1.2%	2.8%	1.2%	n/a	2.25%

The prediction-uncertainties for case M3 may be regarded as the uncertainties of the full-scale predictions obtained using standard submarine model testing in the tow-tank for a specified full-scale submarine and propeller geometry and specified full-scale conditions. However, comparison of full-scale predictions to measurements in full-scale trials introduces additional uncertainties. These additional uncertainties, called full-scale uncertainties hereafter, stem from the uncertainties in the values of the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, and the values of the full-scale speed, propeller rpm, thrust, torque, and shaft horsepower. The contribution of these full-scale uncertainties to the prediction-uncertainties is considered in case F.

Case F : contribution of full-scale uncertainties

All model-scale uncertainties are ignored in case F, which only considers the contribution of full-scale uncertainties. Thus, all model-scale variables, and the correlation allowance, are presumed known without uncertainty in case F.

The relative uncertainties of the density and the viscosity of sea water, of the length and the wetted-surface area of the full-scale submarine, and of the propeller diameter are taken as is indicated in the following table :

Uncertainties of full-scale input variables

density	viscosity	length	area	prop diameter
1%	2%	0.5%	1%	0.1%

The uncertainties of full-scale measurements are considered in Appendix E . The total (precision + bias) uncertainties of full-scale measurements are taken as

Uncertainties of full-scale measurements

speed	rpm	thrust	torque	SHP
0.6%	0.4%	3.0%	0.9%	0.9%

hereafter.

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the foregoing full-scale uncertainties are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP .

Full-scale prediction-uncertainties for case F

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	0.75%	3.5%	2.05%	2.45%	2.25%
rpm	0.75%	0.40%	3.4%	1.85%	2.05%	1.85%
thrust	1.8%	1.75%	3.0%	3.15%	4.7%	4.6%
torque	1.05%	0.95%	3.15%	0.9%	1.8%	1.55%
SHP	0.85%	0.7%	3.1%	1.2%	0.9%	0.9%

The prediction-uncertainties for case F, which only considers the contribution of full-scale uncertainties (with all other sources of uncertainties ignored), are roughly comparable (although somewhat smaller on the whole) to the uncertainties for case M3, which only considers the contribution of model-scale uncertainties (with all other sources of uncertainties ignored).

Case MF : contribution of model-scale and full-scale uncertainties

The contributions of both the model-scale uncertainties and the full-scale uncertainties considered in cases M3 and F, respectively, are now combined. The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP for this case, called MF hereafter, are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP .

Full-scale prediction-uncertainties for case MF

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	0.85%	4.8%	3.9%	4.1%	3.25%
rpm	0.85%	0.4%	4.8%	4.0%	4.1%	3.3%
thrust	2.45%	2.5%	3.0%	4.5%	6.35%	5.85%
torque	2.0%	2.1%	4.5%	0.9%	2.55%	2.1%
SHP	1.4%	1.4%	4.15%	1.7%	0.9%	2.45%

The uncertainties for case MF are larger than the uncertainties for either case M3 or case F, as one expects.

Case MFC : sensitivity to variations in the correlation allowance

The prediction-uncertainties for case MF are based on the assumption that the correlation allowance is known without uncertainty. However, variations in the value of the correlation allowance occur, due to variations in the full-scale submarine that are not accounted for in the model tests (e.g. variations in the hull roughness) as well as uncertainties attached to both model-scale and full-scale variables. As is noted in the introduction, bias errors systematically introduced at model scale and full scale are largely, although not fully, included in the correlation allowance.

The correlation allowance is taken equal to 0.0005 for the typical case examined in the present uncertainty analysis. Experience with the SSN 688 class submarines indicates variations of the correlation allowance within a fairly broad range. Inasmuch as the contributions of model-scale and full-scale uncertainties are already included in the full-scale prediction-uncertainties obtained in case MF, a 20% variation of the correlation allowance is considered here, i.e. variations of the correlation allowance CA within the range

$$CA = 0.0005 +/- 0.0001$$

are considered in case MFC . Thus, the prediction-uncertainties obtained when the effect of a 20% variation in the value of the correlation allowance is added to the model-scale and full-scale uncertainties considered in case MF is examined in case MFC .

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP for this case, called case MFC, are listed in the next table for five cases corresponding to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP .

Full-scale prediction-uncertainties for case MFC

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	0.85%	6.0%	5.35%	5.45%	4.9%
rpm	0.85%	0.4%	6.0%	5.4%	5.5%	4.9%
thrust	3.1%	3.1%	3.0%	4.5%	6.6%	6.15%
torque	2.75%	2.8%	4.5%	0.9%	3.2%	2.8%
SHP	1.85%	1.85%	4.35%	2.1%	0.9%	2.45%

The uncertainties for case MFC are larger than the uncertainties for case MF, as one expects.

CONCLUSION

In summary, a tool for estimating the uncertainties attached to full-scale predictions of submarine resistance and propulsion based on standard submarine tow-tank model tests has been developed, using a global uncertainty analysis, and applied to a typical case. The analysis takes into account the uncertainties associated with the prediction procedure and the uncertainties of measurements performed both at model scale and at full scale. Thus, the uncertainty analysis developed and applied here takes into account all the component uncertainties which influence the overall uncertainty of full-scale predictions.

Estimates of the prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP attached to the full-scale speed, rpm, thrust, torque, SHP and EHP have been obtained for five cases, which correspond to predictions for a specified value of the full-scale speed, rpm, thrust, torque or SHP. The prediction-uncertainties for a specified value of the full-scale shaft horsepower are on the whole somewhat smaller than the prediction-uncertainties corresponding to a specified value of the full-scale speed, rpm, thrust, or torque. Estimates of the prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP are given for six cases, called M1, M2, M3, F, MF and MFC.

The prediction-uncertainties for case M1 represent the contribution of precision errors of model-scale measurements when all other sources of errors (including bias errors of model-scale measurements, uncertainties of the density and the viscosity of tank water, and model-scale geometrical inaccuracies) are ignored. Thus, bias errors attached to the measured primary model-scale variables are not taken into account in case M1, which corresponds to successive model tests within a series of consecutive tests.

The contribution of uncertainties of the density and the viscosity of tank water, the model length and area, and the propeller diameter, are considered in case

M2. The uncertainties of full-scale predictions for case M2 are not appreciably larger than those obtained for case M1. Thus, the uncertainties of the density and the viscosity of tank water, of the length and the area of the model, and of the diameter of the propeller are sufficiently small that they have insignificant effect upon the prediction-uncertainties.

The sensitivity of prediction-uncertainties to model-scale bias errors is considered in case M3. Model-scale bias errors are taken equal to the model-scale precision (random) errors considered in cases M1 and M2. Thus, the prediction-uncertainties for case M3 are equal to $2^{1/2}$ times the prediction-uncertainties for case M2 as one expects. The prediction-uncertainties for case M3 may be regarded as the uncertainties of the full-scale predictions obtained using standard submarine model testing in the tow-tank for a specified full-scale submarine and propeller geometry and specified full-scale conditions.

Comparison of full-scale predictions to measurements in full-scale trials introduces additional uncertainties. These additional full-scale uncertainties stem from the uncertainties in the values of the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, and the values of the full-scale speed, propeller rpm, thrust, torque, and shaft horsepower. The contribution of these full-scale uncertainties to the prediction-uncertainties is considered in case F , which only considers the contribution of full-scale uncertainties (with all other sources of uncertainties ignored). The prediction-uncertainties for case F are roughly comparable (although somewhat smaller on the whole) to the uncertainties for case M3, which only considers the contribution of model-scale uncertainties (with all other sources of uncertainties ignored).

The contributions of both the model-scale uncertainties and the full-scale uncertainties considered in cases M3 and F , respectively, are combined in case MF. Thus, the uncertainties for case MF are larger than the uncertainties for either case

M3 or case F . The prediction-uncertainties for case MF are based on the assumption that the correlation allowance is known without uncertainty.

However, variations in the value of the correlation allowance occur, due to variations in the full-scale submarine (such as variations in the hull roughness) that are not accounted for in the model tests, as well as uncertainties attached to both model-scale and full-scale variables. As is noted in the introduction, bias errors systematically introduced by the prediction procedure and measurements at model scale and full scale are largely, although not fully, included in the correlation allowance. Inasmuch as the contributions of model-scale and full-scale uncertainties are already included in the full-scale prediction-uncertainties evaluated in case MF, the effect of a 20% variation in the value of the correlation allowance added to the model-scale and full-scale uncertainties determined in case MF is examined in case MFC .

The cases M1, M2, M3, F, MF and MFC are summarized below

Cases M1, M2, M3, F, MF and MFC

M1	only considers precision uncertainties of model-scale measurements
M2	adds uncertainties of tank-water properties and model-scale geometry
M3	considers all model-scale precision and bias uncertainties
F	only considers full-scale uncertainties
MF	considers all model-scale and full-scale uncertainties
MFC	adds sensitivity to variations in correlation allowance

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for a specified value of the full-scale SHP are listed in the following table for the six cases M1, M2, M3, F, MF and MFC. The uncertainty UPC of the propulsive efficiency is also given in the table

Full-scale prediction-uncertainties for a specified SHP

case	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP	UPC
M1	0.7%	0.8%	2.0%	0.8%	n/a	1.6%	1.6%
M2	0.8%	0.9%	2.0%	0.9%	n/a	1.6%	1.6%
M3	1.1%	1.2%	2.8%	1.2%	n/a	2.3%	2.3%
F	0.8%	0.7%	3.1%	1.2%	0.9%	0.9%	n/a
MF	1.4%	1.4%	4.2%	1.7%	0.9%	2.4%	2.3%
MFC	1.9%	1.9%	4.3%	2.1%	0.9%	2.4%	2.3%

In summary, it may be concluded that the full-scale prediction-uncertainties for a specified SHP are approximately equal to

Summary of full-scale prediction-uncertainties for a specified SHP

Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP	UPC
2%	2%	4%	2%	1%	2%	2%

APPENDIX A : PREDICTION PROCEDURE

Primary model-scale variables

Primary model-scale variables are determined from measurements. Five major primary variables are measured : the carriage speed V, the drag R, and the propeller rps n, thrust T and torque Q.

Transformed model-scale variables

Transformed model-scale variables are obtained from the measured primary variables by means of analytical relations. The major transformed model-scale variables are the total-drag coefficient C_T, the friction-drag coefficient C_F, the residuary-drag coefficient C_R, the advance ratio J_V, the thrust-deduction factor $1-t$ and the propulsive efficiency η_D. The relations defining these transformed variables are given below.

The total-drag coefficient C_T of the model in a resistance (EHP) test is given by the relation

$$C_T = \frac{R_T}{\rho S V^2/2} \tag{1}$$

where R_T is the drag of the model (without propeller), ρ is the density of the tank water, S is the wetted-surface area of the model, and V is the carriage speed. The friction-drag coefficient C_F of the model is evaluated using the ITTC formula

$$C_F = 0.075/(C\ln R_n - 2)^2 \tag{2a}$$

where $C \simeq 0.4342944819$. The Reynolds number R_n is defined as

$$R_n = VL/\nu \tag{2b}$$

where L is the length of the model and ν is the kinematic viscosity of the tank water. The residuary-drag coefficient C_R is defined by the relation

$$C_R = C_T - C_F \tag{3}$$

where C_T and C_F are given by (1) and (2), respectively. The residuary-drag coefficient C_R is evaluated at low speed, so that free-surface effects may be neglected.

Propulsion tests yield the ideal resistance R_i

$$R_i = R_T - \Delta R \tag{4}$$

where R_T is the drag of the model without propeller and ΔR is the change in the tow force due to the propeller. The total-drag coefficient C_T of the model in a propulsion test is given by

$$C_T = \frac{R_i}{\rho S V^2/2} \tag{5}$$

The advance ratio J_V is defined as

$$J_V = V/(nD) \tag{6}$$

where n and D are the propeller *rps* and diameter. The thrust-deduction factor $1-t$ is given by

$$1 - t = R_i \,/\, T \tag{7}$$

where T is the propeller thrust. The propulsive efficiency η_D is

$$\eta_D = \frac{V R_i}{2\pi\, n\, Q} \tag{8}$$

where Q is the propeller torque. The three curves representing the nondimensional variables J_V, $1-t$ and η_D as functions of C_T are used to determine full-scale predictions.

Full-scale predictions

The superscript S identifies full-scale variables. No superscript is used for model-scale variables. At a given ship speed V^S, the total-drag coefficient C_T^S, the propeller rps n^S, thrust T^S and torque Q^S, and the shaft horsepower SHP^S are determined using the relations given below.

The friction-drag coefficient C_F^S is determined using the ITTC formula

$$C_F^S = 0.075/(C \ln R_n^S - 2)^2 \tag{9a}$$

where $C \simeq 0.4342944819$. The Reynolds number R_n^S is defined as

$$R_n^S = V^S L^S / \nu^{sea} \tag{9b}$$

where L^S is the ship length and ν^{sea} is the kinematic viscosity of sea water. The total-drag coefficient C_T^S of the ship is evaluated using the relation

$$C_T^S = C_F^S + C_R + C_A \tag{10}$$

Here, C_F^S is the friction-drag coefficient, C_R is the residuary-drag coefficient determined from model tests, and the correlation allowance C_A accounts for differences between the actual drag coefficient C_T^S and the predicted drag coefficient $C_F^S + C_R$.

The propeller rps is obtained from the relation

$$n^S = \frac{V^S}{J_V^S\, D^S} \tag{11}$$

where D^S is the propeller diameter. Furthermore, the advance ratio J_V^S is determined from the function $J_V(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S predicted by (10).

The total drag of the ship R_T^S and the power required to overcome R_T^S are given by

$$R_T^S = C_T^S\, \rho^{sea}\, S^S (V^S)^2/2$$

$$EHP^S = R_T^S\, V^S = C_T^S\, \rho^{sea}\, S^S (V^S)^3/2 \tag{12}$$

where ρ^{sea} is the density of sea water and S^S is the wetted surface of the ship.

The thrust T^S exerted by the propeller is evaluated using the relation

$$T^S = \frac{R_T^S}{1-t^S} = \frac{C_T^S}{1-t^S}\,\rho^{sea}\,S^S(V^S)^2/2 \tag{13}$$

where the thrust-deduction factor $1-t^S$ is determined from the function $(1-t)(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S given by (10).

The power provided to the propeller is

$$SHP^S = \frac{EHP^S}{\eta_D^S} = \frac{C_T^S}{\eta_D^S}\,\rho^{sea}\,S^S(V^S)^3/2 \tag{14}$$

where the propulsive efficiency η_D^S is determined from the function $\eta_D(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S given by (10).

Finally, the propeller torque Q^S is defined by

$$Q^S = \frac{SHP^S}{2\pi\, n^S} = \frac{C_T^S\, J_V^S D^S}{4\pi\,\eta_D^S}\,\rho^{sea}\,S^S(V^S)^2 \tag{15}$$

where (14) and (11) were used.

The foregoing relations yield values of the shaft horsepower SHP^S corresponding to a range of values of the ship speed V^S. A plot of the speed V^S as a function of the horsepower SHP^S is then used to determine the ship speed V^S corresponding to a prescribed value of the power SHP^S.

APPENDIX B : GLOBAL UNCERTAINTY ANALYSIS

Uncertainties of measured model-scale variables

The previous relations, which define model-scale and full-scale variables in terms of five measured primary model-scale variables (speed V, drag R, and propeller rps n, thrust T and torque Q), can be used to determine the uncertainties of the transformed model-scale variables and of the predicted full-scale variables in terms of the uncertainties of the measured primary variables. These analytical expressions for the uncertainties of the transformed model-scale variables and of the full-scale predictions are given below.

Uncertainties of transformed model-scale variables

Expression (1) yields

$$\frac{dC_T}{C_T} = \frac{dR_T}{R_T} - \frac{d\rho}{\rho} - \frac{dS}{S} - 2\,\frac{dV}{V} \tag{16}$$

Using (2) we obtain

$$\frac{dC_F}{C_F} = \frac{-2\,C}{C\ln R_n - 2}\,\frac{dR_n}{R_n} = \frac{-2\,C}{\sqrt{0.075}}\sqrt{C_F}\left(\frac{dV}{V} + \frac{dL}{L} - \frac{d\nu}{\nu}\right) = -\sqrt{\widehat{C}\,C_F}\left(\frac{dV}{V} + \frac{dL}{L} - \frac{d\nu}{\nu}\right)$$

where $\widehat{C} = 4\,C^2/0.075 \simeq 10.0593$. We thus have

$$\frac{dC_F}{C_F} = -\sqrt{10\,C_F}\left(\frac{dV}{V} + \frac{dL}{L} - \frac{d\nu}{\nu}\right) \tag{17}$$

Expression (3) yields

$$dC_R = C_T\,\frac{dC_T}{C_T} - C_F\,\frac{dC_F}{C_F}$$

By using (16) and (17) we obtain

$$dC_R = C_T\left(\frac{dR_T}{R_T} - \frac{d\rho}{\rho} - \frac{dS}{S}\right) + C_F\sqrt{10\,C_F}\left(\frac{dL}{L} - \frac{d\nu}{\nu}\right) - \left(2\,C_T - C_F\sqrt{10\,C_F}\right)\frac{dV}{V}$$

Thus, the uncertainty of the residuary-drag coefficient is defined by

$$\left(\frac{\delta C_R}{C_T}\right)^2 = \left(\frac{\delta R}{R_T}\right)^2 + \left(\frac{\delta\rho}{\rho}\right)^2 + \left(\frac{\delta S}{S}\right)^2 + 10\,C_F\left(\frac{C_F}{C_T}\right)^2\left[\left(\frac{\delta L}{L}\right)^2 + \left(\frac{\delta\nu}{\nu}\right)^2\right] + \left(2 - \sqrt{10\,C_F}\,\frac{C_F}{C_T}\right)^2\left(\frac{\delta V}{V}\right)^2 \tag{18}$$

where δR stands for δR_T and V is the carriage speed for the resistance test used to determine C_R.

Expression (4) yields

$$dR_i = dR_T - d\Delta R$$

The absolute uncertainty of R_i therefore is given by

$$\delta R_i = \sqrt{\left(\frac{\delta R_T}{R_T}\right)^2 (R_T)^2 + \left(\frac{\delta \Delta R}{\Delta R}\right)^2 (\Delta R)^2} \tag{19}$$

Expression (5) shows that the relative uncertainty of C_T is given by

$$\left(\frac{\delta C_T}{C_T}\right)^2 = \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta S}{S}\right)^2 + 4\left(\frac{\delta V}{V}\right)^2 \tag{20}$$

Expression (6) defines the relative uncertainty of the advance ratio J_V as

$$\left(\frac{\delta J_V}{J_V}\right)^2 = \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta n}{n}\right)^2 + \left(\frac{\delta D}{D}\right)^2 \tag{21}$$

The relative uncertainty of the thrust-deduction factor $1-t$ is defined by (7) as

$$\left(\frac{\delta(1-t)}{1-t}\right)^2 = \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta T}{T}\right)^2 \tag{22}$$

The relative uncertainty of the propulsive efficiency η_D is defined by (8) as

$$\left(\frac{\delta \eta_D}{\eta_D}\right)^2 = \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta n}{n}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2 \tag{23}$$

In (20) and (22)-(23), δR_i is given by (19).

Uncertainties of full-scale predictions

Expression (10) for the total-drag coefficient C_T^S yields

$$dC_T^S = dC_F^S + dC_R + dC_A$$

which may be expressed in the form

$$\frac{dC_T^S}{C_T^S} = \frac{C_F^S}{C_T^S}\frac{dC_F^S}{C_F^S} + \frac{dC_R + dC_A}{C_T^S}$$

Expressions (9), (2) and (17) show that we have

$$\frac{dC_F^S}{C_F^S} = -\sqrt{10\,C_F^S}\left(\frac{dV^S}{V^S} + \frac{dL^S}{L^S} - \frac{d\nu^{sea}}{\nu^{sea}}\right) \tag{24}$$

We then have

$$\frac{dC_T^S}{C_T^S} = \Gamma\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right) \tag{25}$$

where Γ and $D_C^{L\nu}$ are defined as

$$\Gamma = \sqrt{10\,C_F^S}\,\frac{C_F^S}{C_T^S} \tag{26}$$

$$D_C^{L\nu} = \frac{dC_R + dC_A}{\sqrt{10\,C_F^S}\,C_F^S} - \frac{dL^S}{L^S} + \frac{d\nu^{sea}}{\nu^{sea}} \tag{27}$$

Expressions (11), (13), (14) and (15) involve the nondimensional coefficients J_V, $1-t$ and η_D. These coefficients are determined from curve fits (obtained from model tests) of J_V, $1-t$

and η_D as functions of C_T. Let Λ stand for any one of the three coefficients J_V, $1{-}t$ and η_D. The difference in the coefficient Λ is given by

$$d\Lambda\,|_{C_T^S} + \frac{d\Lambda}{d\,C_T}\,dC_T^S$$

The first term represents the difference in Λ at a given value of C_T^S, and the second term defines the difference in Λ due to the uncertainty of C_T^S. Let the first term be written as $d\Lambda$ for shortness. The relative difference in Λ may then be expressed in the form

$$\frac{d\Lambda}{\Lambda} + \frac{d\Lambda}{d\,C_T}\,\frac{C_T^S}{\Lambda}\,\Gamma\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right)$$

where (25) was used. The relative differences in the coefficients J_V, $1{-}t$ and η_D are then given by

$$\frac{dJ_V}{J_V} + \sigma^J\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right) \qquad \frac{d(1{-}t)}{1{-}t} + \sigma^t\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right) \qquad \frac{d\eta_D}{\eta_D} + \sigma^\eta\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right) \tag{28}$$

where σ^J, σ^t and σ^η are defined as

$$\sigma^J = \sqrt{10\,C_F^S}\,\frac{C_F^S}{J_V}\,\frac{dJ_V}{dC_T} \qquad \sigma^t = \sqrt{10\,C_F^S}\,\frac{C_F^S}{1{-}t}\,\frac{d(1{-}t)}{dC_T} \qquad \sigma^\eta = \sqrt{10\,C_F^S}\,\frac{C_F^S}{\eta_D}\,\frac{d\eta_D}{dC_T} \tag{29}$$

Here, expression (26) for the term Γ was used.

It is also useful to define the notation

$$D_V = \frac{dV^S}{V^S} \qquad D_N = \frac{dn^S}{n^S} \qquad D_T = \frac{dT^S}{T^S} \qquad D_Q = \frac{dQ^S}{Q^S} \qquad D_P = \frac{dSHP^S}{SHP^S} \tag{30a}$$

$$D_\rho^S = \frac{d\rho^{sea}}{\rho^{sea}} + \frac{dS^S}{S^S} \qquad D_t = \frac{d(1-t)}{1-t} \qquad D_\eta = \frac{d\eta_D}{\eta_D} \qquad D_J^D = \frac{dJ_V}{J_V} + \frac{dD^S}{D^S} \tag{30b}$$

Expressions (11), (13), (14), (15), (25), (28) and (30) yield

$$D_N = (\,1+\sigma^J\,)\,D_V - \sigma^J D_C^{L\nu} - D_J^D \tag{31a}$$

$$D_T = (\,2-\Gamma+\sigma^t\,)\,D_V + (\,\Gamma-\sigma^t\,)\,D_C^{L\nu} + D_\rho^S - D_t \tag{31b}$$

$$D_Q = (\,2-\Gamma+\sigma^\eta-\sigma^J\,)\,D_V + (\,\Gamma-\sigma^\eta+\sigma^J\,)\,D_C^{L\nu} + D_\rho^S - D_\eta + D_J^D \tag{31c}$$

$$D_P = (\,3-\Gamma+\sigma^\eta\,)\,D_V + (\,\Gamma-\sigma^\eta\,)\,D_C^{L\nu} + D_\rho^S - D_\eta \tag{31d}$$

where the relative differences dJ_V^S/J_V^S, $d(1-t^S)/(1-t^S)$ and $d\eta_D^S/\eta_D^S$ have been taken equal to the corresponding model-scale values dJ_V/J_V, $d(1-t)/(1-t)$ and $d\eta_D/\eta_D$.

The four relations (31) involve model-scale variables and differences — which occur via expressions (18), (21), (22), (23) for the terms dC_R, dJ_V/J_V, $d(1-t)/(1-t)$, $d\eta_D/\eta_D$ — and full-scale variables. The full-scale variables include the relative differences $d\rho^{sea}/\rho^{sea}$, $d\nu^{sea}/\nu^{sea}$, dD^S/D^S, dL^S/L^S and dS^S/S^S (which may be determined independently and thus may be presumed known for the purpose of this uncertainty analysis), the difference dC_A (which may also be regarded as a given input for this analysis), and the five terms dV^S/V^S,

dn^S/n^S, dT^S/T^S, dQ^S/Q^S, $dSHP^S/SHP^S$. Thus, four of these five terms may be determined from any one of them. Specifically, the four relations (31), which define the relative differences dn^S/n^S, dT^S/T^S, dQ^S/Q^S and $dSHP^S/SHP^S$ in terms of dV^S/V^S, can be expressed in the four alternative forms given below.

One alternative form of the four relations (31) is

$$(1+\sigma^J)\,D_V = D_N + \sigma^J D_C^{L\nu} + D_J^D \tag{32a}$$

$$\begin{aligned}(1+\sigma^J)\,D_T = {} & (2-\Gamma+\sigma^t)(D_N + D_J^D) \\ & +(\Gamma-\sigma^t+2\sigma^J)\,D_C^{L\nu} + (1+\sigma^J)(D_\rho^S - D_t)\end{aligned} \tag{32b}$$

$$\begin{aligned}(1+\sigma^J)\,D_Q = {} & (2-\Gamma+\sigma^\eta-\sigma^J)\,D_N + (\Gamma-\sigma^\eta+3\sigma^J)\,D_C^{L\nu} \\ & +(1+\sigma^J)(D_\rho^S - D_\eta) + (3-\Gamma+\sigma^\eta)\,D_J^D\end{aligned} \tag{32c}$$

$$\begin{aligned}(1+\sigma^J)\,D_P = {} & (3-\Gamma+\sigma^\eta)(D_N + D_J^D) + (\Gamma-\sigma^\eta+3\sigma^J)\,D_C^{L\nu} \\ & +(1+\sigma^J)(D_\rho^S - D_\eta)\end{aligned} \tag{32d}$$

These relations define the relative differences dV^S/V^S, dT^S/T^S, dQ^S/Q^S and $dSHP^S/SHP^S$ in terms of dn^S/n^S.

The four relations (31) can similarly be expressed in the form

$$(2-\Gamma+\sigma^t)\,D_V = D_T - (\Gamma-\sigma^t)\,D_C^{L\nu} - D_\rho^S + D_t \tag{33a}$$

$$\begin{aligned}(2-\Gamma+\sigma^t)\,D_N = {} & (1+\sigma^J)(D_T - D_\rho^S + D_t) - (\Gamma-\sigma^t+2\sigma^J)\,D_C^{L\nu} \\ & -(2-\Gamma+\sigma^t)\,D_J^D\end{aligned} \tag{33b}$$

$$\begin{aligned}(2-\Gamma+\sigma^t)\,D_Q = {} & (2-\Gamma+\sigma^\eta-\sigma^J)(D_T + D_t) \\ & +(\sigma^t-\sigma^\eta+\sigma^J)(2D_C^{L\nu} + D_\rho^S) + (2-\Gamma+\sigma^t)(D_J^D - D_\eta)\end{aligned} \tag{33c}$$

$$\begin{aligned}(2-\Gamma+\sigma^t)\,D_P = {} & (3-\Gamma+\sigma^\eta)(D_T + D_t) - (\Gamma+2\sigma^\eta-3\sigma^t)\,D_C^{L\nu} \\ & -(1+\sigma^\eta-\sigma^t)\,D_\rho^S - (2-\Gamma+\sigma^t)\,D_\eta\end{aligned} \tag{33d}$$

These relations define the relative differences dV^S/V^S, dn^S/n^S, dQ^S/Q^S and $dSHP^S/SHP^S$ in terms of dT^S/T^S.

A third alternative form of the four relations (31) is

$$(2-\Gamma+\sigma^\eta-\sigma^J)\,D_V = D_Q - (\Gamma-\sigma^\eta+\sigma^J)\,D_C^{L\nu} - D_\rho^S + D_\eta - D_J^D \tag{34a}$$

$$\begin{aligned}(2-\Gamma+\sigma^\eta-\sigma^J)\,D_N = {} & (1+\sigma^J)(D_Q - D_\rho^S + D_\eta) - (\Gamma-\sigma^\eta+3\sigma^J)\,D_C^{L\nu} \\ & -(3-\Gamma+\sigma^\eta)\,D_J^D\end{aligned} \tag{34b}$$

$$(2-\Gamma+\sigma^\eta-\sigma^J)\,D_T=(2-\Gamma+\sigma^t)(D_Q+D_\eta-D_J^D)-(\sigma^t-\sigma^\eta+\sigma^J)(2D_C^{L\nu}+D_\rho^S)$$
$$-(2-\Gamma+\sigma^\eta-\sigma^J)\,D_t \tag{34c}$$

$$(2-\Gamma+\sigma^\eta-\sigma^J)\,D_P=(3-\Gamma+\sigma^\eta)(D_Q-D_J^D)-(\Gamma-\sigma^\eta+3\,\sigma^J)\,D_C^{L\nu}$$
$$-(1+\sigma^J)(D_\rho^S-D_\eta) \tag{34d}$$

These relations define the relative differences dV^S/V^S, dn^S/n^S, dT^S/T^S and $dSHP^S/SHP^S$ in terms of dQ^S/Q^S.

Finally, the four relations (31) can be expressed as

$$(3-\Gamma+\sigma^\eta)\,D_V=D_P-(\Gamma-\sigma^\eta)\,D_C^{L\nu}-D_\rho^S+D_\eta \tag{35a}$$

$$(3-\Gamma+\sigma^\eta)\,D_N=(1+\sigma^J)(D_P-D_\rho^S+D_\eta)-(\Gamma-\sigma^\eta+3\,\sigma^J)\,D_C^{L\nu}$$
$$-(3-\Gamma+\sigma^\eta)\,D_J^D \tag{35b}$$

$$(3-\Gamma+\sigma^\eta)\,D_T=(2-\Gamma+\sigma^t)(D_P+D_\eta)+(\Gamma+2\,\sigma^\eta-3\,\sigma^t)\,D_C^{L\nu}$$
$$+(1+\sigma^\eta-\sigma^t)\,D_\rho^S-(3-\Gamma+\sigma^\eta)\,D_t \tag{35c}$$

$$(3-\Gamma+\sigma^\eta)\,D_Q=(2-\Gamma+\sigma^\eta-\sigma^J)\,D_P+(\Gamma-\sigma^\eta+3\,\sigma^J)\,D_C^{L\nu}$$
$$+(1+\sigma^J)(D_\rho^S-D_\eta)+(3-\Gamma+\sigma^\eta)\,D_J^D \tag{35d}$$

These relations define the relative differences dV^S/V^S, dn^S/n^S, dT^S/T^S and dQ^S/Q^S in terms of $dSHP^S/SHP^S$.

Expressions (12) and (14) show that the relative difference

$$D_E=\frac{dEHP^S}{EHP^S} \tag{36}$$

can be obtained from the foregoing expressions for the relative difference $D_P=dSHP^S/SHP^S$. Specifically, expressions (31d), (32d), (33d) and (34d) respectively yield

$$D_E=(3-\Gamma)\,D_V+\Gamma\,D_C^{L\nu}+D_\rho^S \tag{37a}$$

$$(1+\sigma^J)\,D_E=(3-\Gamma)(D_N+D_J^D)+(\Gamma+3\,\sigma^J)\,D_C^{L\nu}+(1+\sigma^J)\,D_\rho^S \tag{37b}$$

$$(2-\Gamma+\sigma^t)\,D_E=(3-\Gamma)(D_T+D_t)-(\Gamma-3\,\sigma^t)\,D_C^{L\nu}-(1-\sigma^t)\,D_\rho^S \tag{37c}$$

$$(2-\Gamma-\sigma^J)\,D_E=(3-\Gamma)(D_Q-D_J^D)-(\Gamma+3\,\sigma^J)\,D_C^{L\nu}-(1+\sigma^J)D_\rho^S \tag{37d}$$

The relations $EHP^S=\eta_D\,SHP^S$, (28) and (35a) yield

$$(3-\Gamma+\sigma^\eta)\,D_E=(3-\Gamma)(D_P+D_\eta)+\sigma^\eta\,(3D_C^{L\nu}+D_\rho^S) \tag{37e}$$

The relative uncertainties $\delta V^S/V^S$, $\delta n^S/n^S$, $\delta T^S/T^S$, $\delta Q^S/Q^S$ and $\delta SHP^S/SHP^S$ corresponding to the relative differences dV^S/V^S, dn^S/n^S, dT^S/T^S, dQ^S/Q^S and $dSHP^S/SHP^S$

defined in the foregoing alternative relations are readily determined by taking the square root of the sum of the square of every term in these relations. Thus, we define the notation

$$U_C^{L\nu} = \frac{(\delta C_R)^2 + (\delta C_A)^2}{10\,(C_F^S)^3} + \left(\frac{\delta L^S}{L^S}\right)^2 + \left(\frac{\delta \nu^{sea}}{\nu^{sea}}\right)^2 \qquad U_\rho^S = \left(\frac{\delta \rho^{sea}}{\rho^{sea}}\right)^2 + \left(\frac{\delta S^S}{S^S}\right)^2 \tag{38a}$$

$$U_V = \left(\frac{\delta V^S}{V^S}\right)^2 \qquad U_N = \left(\frac{\delta n^S}{n^S}\right)^2 \qquad U_T = \left(\frac{\delta T^S}{T^S}\right)^2 \qquad U_Q = \left(\frac{\delta Q^S}{Q^S}\right)^2 \tag{38b}$$

$$U_P = \left(\frac{\delta SHP^S}{SHP^S}\right)^2 \qquad U_E = \left(\frac{\delta EHP^S}{EHP^S}\right)^2 \qquad U_t = \left(\frac{\delta(1-t)}{1-t}\right)^2 \tag{38c}$$

$$U_\eta = \left(\frac{\delta \eta_D}{\eta_D}\right)^2 \qquad U_J^D = \left(\frac{\delta J_V}{J_V}\right)^2 + \left(\frac{\delta D^S}{D^S}\right)^2 \tag{38d}$$

corresponding to (27) and (30). We also define the relative uncertainties attached to the full-scale measurements of V^S, n^S, T^S, Q^S, SHP^S and EHP^S, i.e.

$$U_V^{fsm} = \left(\frac{\delta V_{fsm}^S}{V^S}\right)^2 \qquad U_N^{fsm} = \left(\frac{\delta n_{fsm}^S}{n^S}\right)^2 \qquad U_T^{fsm} = \left(\frac{\delta T_{fsm}^S}{T^S}\right)^2 \tag{38e}$$

$$U_Q^{fsm} = \left(\frac{\delta Q_{fsm}^S}{Q^S}\right)^2 \qquad U_P^{fsm} = \left(\frac{\delta SHP_{fsm}^S}{SHP^S}\right)^2 \qquad U_E^{fsm} = \left(\frac{\delta EHP_{fsm}^S}{EHP^S}\right)^2 \tag{38f}$$

where the subscript or superscript *fsm* means *full-scale measurement.* In practice, the uncertainty U_E^{fsm} attached to the effective horsepower EHP^S of the ship is not defined because measurements of EHP_{fsm}^S are not available. Thus, the term EHP_{fsm}^S in the expressions given below may be ignored in practice.

Expressions (31) and (37a) yield

$$U_N = (1+\sigma^J)^2\, U_V^{fsm} + (\sigma^J)^2\, U_C^{L\nu} + U_J^D + U_N^{fsm} \tag{39a}$$

$$U_T = (2-\Gamma+\sigma^t)^2\, U_V^{fsm} + (\Gamma-\sigma^t)^2\, U_C^{L\nu} + U_\rho^S + U_t + U_T^{fsm} \tag{39b}$$

$$U_Q = (2-\Gamma+\sigma^\eta-\sigma^J)^2\, U_V^{fsm} + (\Gamma-\sigma^\eta+\sigma^J)^2\, U_C^{L\nu} + U_\rho^S + U_\eta + U_J^D + U_Q^{fsm} \tag{39c}$$

$$U_P = (3-\Gamma+\sigma^\eta)^2\, U_V^{fsm} + (\Gamma-\sigma^\eta)^2\, U_C^{L\nu} + U_\rho^S + U_\eta + U_P^{fsm} \tag{39d}$$

$$U_E = (3-\Gamma)^2\, U_V^{fsm} + \Gamma^2\, U_C^{L\nu} + U_\rho^S + U_E^{fsm} \tag{39e}$$

Similarly, (32) and (37b) yield

$$(1+\sigma^J)^2\, U_V = U_N^{fsm} + (\sigma^J)^2\, U_C^{L\nu} + U_J^D + (1+\sigma^J)^2\, U_V^{fsm} \tag{40a}$$

$$\begin{aligned}(1+\sigma^J)^2\, U_T = {} & (2-\Gamma+\sigma^t)^2\,(U_N^{fsm} + U_J^D) + (\Gamma-\sigma^t+2\,\sigma^J)^2\, U_C^{L\nu} \\ & + (1+\sigma^J)^2\,(U_\rho^S + U_t + U_T^{fsm})\end{aligned} \tag{40b}$$

$$(1+\sigma^J)^2 U_Q = (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_N^{fsm} + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} + (3-\Gamma+\sigma^\eta)^2 U_J^D + (1+\sigma^J)^2 (U_\rho^S + U_\eta + U_Q^{fsm}) \tag{40c}$$

$$(1+\sigma^J)^2 U_P = (3-\Gamma+\sigma^\eta)^2 (U_N^{fsm} + U_J^D) + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} + (1+\sigma^J)^2 (U_\rho^S + U_\eta + U_P^{fsm}) \tag{40d}$$

$$(1+\sigma^J)^2 U_E = (3-\Gamma)^2 (U_N^{fsm} + U_J^D) + (\Gamma+3\sigma^J)^2 U_C^{L\nu} + (1+\sigma^J)^2 (U_\rho^S + U_E^{fsm}) \tag{40e}$$

Expressions (33) and (37c) yield

$$(2-\Gamma+\sigma^t)^2 U_V = U_T^{fsm} + (\Gamma-\sigma^t)^2 U_C^{L\nu} + U_\rho^S + U_t + (2-\Gamma+\sigma^t)^2 U_V^{fsm} \tag{41a}$$

$$(2-\Gamma+\sigma^t)^2 U_N = (1+\sigma^J)^2 (U_T^{fsm} + U_\rho^S + U_t) + (\Gamma-\sigma^t+2\sigma^J)^2 U_C^{L\nu} + (2-\Gamma+\sigma^t)^2 (U_J^D + U_N^{fsm}) \tag{41b}$$

$$(2-\Gamma+\sigma^t)^2 U_Q = (2-\Gamma+\sigma^\eta-\sigma^J)^2 (U_T^{fsm} + U_t) + (\sigma^t-\sigma^\eta+\sigma^J)^2 (4U_C^{L\nu} + U_\rho^S) + (2-\Gamma+\sigma^t)^2 (U_J^D + U_\eta + U_Q^{fsm}) \tag{41c}$$

$$(2-\Gamma+\sigma^t)^2 U_P = (3-\Gamma+\sigma^\eta)^2 (U_T^{fsm} + U_t) + (\Gamma+2\sigma^\eta-3\sigma^t)^2 U_C^{L\nu} + (1+\sigma^\eta-\sigma^t)^2 U_\rho^S + (2-\Gamma+\sigma^t)^2 (U_\eta + U_P^{fsm}) \tag{41d}$$

$$(2-\Gamma+\sigma^t)^2 U_E = (3-\Gamma)^2 (U_T^{fsm} + U_t) + (\Gamma-3\sigma^t)^2 U_C^{L\nu} + (1-\sigma^t)^2 U_\rho^S + (2-\Gamma+\sigma^t)^2 U_E^{fsm} \tag{41e}$$

Expressions (34) and (37d) yield

$$(2-\Gamma+\sigma^\eta-\sigma^J)^2 U_V = U_Q^{fsm} + (\Gamma-\sigma^\eta+\sigma^J)^2 U_C^{L\nu} + U_\rho^S + U_\eta + U_J^D + (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_V^{fsm} \tag{42a}$$

$$(2-\Gamma+\sigma^\eta-\sigma^J)^2 U_N = (1+\sigma^J)^2 (U_Q^{fsm} + U_\rho^S + U_\eta) + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} + (3-\Gamma+\sigma^\eta)^2 U_J^D + (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_N^{fsm} \tag{42b}$$

$$(2-\Gamma+\sigma^\eta-\sigma^J)^2 U_T = (2-\Gamma+\sigma^t)^2 (U_Q^{fsm} + U_\eta + U_J^D) + (\sigma^t-\sigma^\eta+\sigma^J)^2 (4U_C^{L\nu} + U_\rho^S) + (2-\Gamma+\sigma^\eta-\sigma^J)^2 (U_t + U_T^{fsm}) \tag{42c}$$

$$(2-\Gamma+\sigma^\eta-\sigma^J)^2 U_P = (3-\Gamma+\sigma^\eta)^2 (U_Q^{fsm} + U_J^D) + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} + (1+\sigma^J)^2 (U_\rho^S + U_\eta) + (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_P^{fsm} \tag{42d}$$

$$(2-\Gamma-\sigma^{J})^{2}\,U_{E}=(3-\Gamma)^{2}\,(U_{Q}^{fsm}+U_{J}^{D})+(\Gamma+3\,\sigma^{J})^{2}\,U_{C}^{L\nu}$$
$$+(1+\sigma^{J})^{2}\,U_{\rho}^{S}+(2-\Gamma-\sigma^{J})^{2}\,U_{E}^{fsm} \qquad (42e)$$

Finally, (35) and (37e) yield

$$(3-\Gamma+\sigma^{\eta})^{2}\,U_{V}=U_{P}^{fsm}+(\Gamma-\sigma^{\eta})^{2}\,U_{C}^{L\nu}+U_{\rho}^{S}+U_{\eta}+(3-\Gamma+\sigma^{\eta})^{2}\,U_{V}^{fsm} \qquad (43a)$$

$$(3-\Gamma+\sigma^{\eta})^{2}\,U_{N}=(1+\sigma^{J})^{2}\,(U_{P}^{fsm}+U_{\rho}^{S}+U_{\eta})+(\Gamma-\sigma^{\eta}+3\,\sigma^{J})^{2}\,U_{C}^{L\nu}$$
$$+(3-\Gamma+\sigma^{\eta})^{2}\,(U_{J}^{D}+U_{N}^{fsm}) \qquad (43b)$$

$$(3-\Gamma+\sigma^{\eta})^{2}\,U_{T}=(2-\Gamma+\sigma^{t})^{2}\,(U_{P}^{fsm}+U_{\eta})+(\Gamma+2\,\sigma^{\eta}-3\,\sigma^{t})^{2}\,U_{C}^{L\nu}$$
$$+(1+\sigma^{\eta}-\sigma^{t})^{2}\,U_{\rho}^{S}+(3-\Gamma+\sigma^{\eta})^{2}\,(U_{t}+U_{T}^{fsm}) \qquad (43c)$$

$$(3-\Gamma+\sigma^{\eta})^{2}\,U_{Q}=(2-\Gamma+\sigma^{\eta}-\sigma^{J})^{2}\,U_{P}^{fsm}+(\Gamma-\sigma^{\eta}+3\,\sigma^{J})^{2}\,U_{C}^{L\nu}$$
$$+(1+\sigma^{J})^{2}\,(U_{\rho}^{S}+U_{\eta})+(3-\Gamma+\sigma^{\eta})^{2}\,(U_{J}^{D}+U_{Q}^{fsm}) \qquad (43d)$$

$$(3-\Gamma+\sigma^{\eta})^{2}\,U_{E}=(3-\Gamma)^{2}\,(U_{P}^{fsm}+U_{\eta})+(\sigma^{\eta})^{2}\,(9\,U_{C}^{L\nu}+U_{\rho}^{S})$$
$$+(3-\Gamma+\sigma^{\eta})^{2}\,U_{E}^{fsm} \qquad (43e)$$

The five sets of alternative expressions (39) through (43), and expressions (38), (29) and (26), define the uncertainties attached to the full-scale predictions of the ship speed V^S, the propeller rpm N^S, thrust T^S and torque Q^S, the shaft horsepower SHP^S and the effective horsepower EHP^S for five cases, in which V^S, N^S, T^S, Q^S or SHP^S are held constant (within the accuracy of full-scale measurements).

APPENDIX C :

FORTRAN-CODE & INPUT-OUTPUT FILES

The source file UA3.f of the program UA3 , which represents the (third version) Fortran implementation of the uncertainty analysis expounded in Appendix B , is given in Appendix C. The symbols defined in the analysis and used in the Fortran-code UA3 are fairly consistent.

An example of the input file UA3.in required by UA3.f , and of the corresponding output file UA3.out generated by UA3.f , is also given in this Appendix. The attached example input file UA3.in and output file UA3.out corresponds to the previously-defined case MFC , in which the uncertainties attached to model-scale and full-scale variables and to the value of the correlation coefficient are included.

FORTRAN CODE

```
c
c      General uncertainty analysis of full-scale resistance
c      and propulsion predictions using tow-tank model tests
c      Francis Noblesse (May 97 ; modified June 97)
c
       program UA3
c
       character TTxp*50 , date*50 , model*50 , prop*50 ,
     &    EHPxp*50 , SHPxp*50 , comment*80
c
       real  ro , nu , Uro , Unu , L , S , D , UL , US , UD , VCRknot ,
     & RTCR , URTCR , Vknot , RT , DelR , nrpm , T , Qinlb ,
     & UV , URT , UDelR , Un , UT , UQ , JVCT , tdCT , etaCT ,
     & nusea , Uros , Unus , LS , VSknot , ULS , USS , UDS ,
     & UVfsm , UNfsm , UTfsm , UQfsm , UPfsm , CA , dCA ,
     & VCR , V , VS , n , Q , CTCR , CFCR , CR , Ri , CT , CF ,
     & JV , td , eta , Uro2 , Unu2 , UL2 , US2 , UD2 , URTCR2 ,
     & UV2 , URi , URi2 , Un2 , UT2 , UQ2 , UCA ,
     & UCTCR2 , UCTCR , UCFCR2 , UCFCR , dCR2 , UCR ,
     & UCT2 , UCT , UCF2 , UCF ,
     & UJV2 , Utd2 , Ueta2,  UJV , Utd , Ueta ,
     & CFS , CTS , UroS2 , UJD2 , cofCFS , UCLnu2 ,
     & Gamma , sigmaJ , sigmat , sigmeta ,
     & UVfsm2 , UNfsm2 , UTfsm2 , UQfsm2 , UPfsm2 ,
     & UN2V , UT2V , UQ2V , UP2V , UE2V ,
     & UVV , UNV , UTV , UQV , UPV , UEV , UAV ,
     & UV2N , UT2N , UQ2N , UP2N , UE2N ,
     & UNN , UVN , UTN , UQN , UPN , UEN , UAN ,
     & UV2T , UN2T , UQ2T , UP2T , UE2T ,
     & UTT , UVT , UNT , UQT , UPT , UET , UAT ,
     & UV2Q , UN2Q , UT2Q , UP2Q , UE2Q ,
     & UQQ , UVQ , UNQ , UTQ , UPQ , UEQ , UAQ ,
     & UV2P , UN2P , UT2P , UQ2P , UE2P ,
     & UPP , UVP , UNP , UTP , UQP , UEP , UAP
c
c      READ INPUT VARIABLES
c
       open(11,file='UA3.in',status='old')
c
       read(11,*) TTxp
       read(11,*) date
       read(11,*) model
```

```
read(11,*) prop
read(11,*) EHPxp
read(11,*) SHPxp
read(11,*)  comment
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) ro , nu
read(11,*)
read(11,*)
read(11,*)
read(11,*) Uro, Unu
read(11,*)
read(11,*)
read(11,*)
read(11,*) L , S , D
read(11,*)
read(11,*)
read(11,*)
read(11,*) UL , US , UD
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) VCRknot , RTCR
read(11,*)
read(11,*)
read(11,*) URTCR
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) Vknot , RT , DelR
read(11,*)
read(11,*)
read(11,*) nrpm , T , Qinlb
read(11,*)
read(11,*)
read(11,*)
read(11,*) UV , URT , UDelR , Un , UT , UQ
read(11,*)
read(11,*)
read(11,*)
read(11,*) JVCT , tdCT , etaCT
```

```
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) nusea
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) Uros , Unus
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) LS , VSknot
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) ULS , USS , UDS
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) UVfsm , UNfsm , UTfsm , UQfsm , UPfsm
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) CA , dCA
c
      close(11,status='keep')
c
c     About notation :
c     U stands for relative Uncertainty
c     fsm stands for Full-Scale Measurement uncertainty
c
c     PRELIMINARY TRANSFORMATIONS
c
c     Rescale nu and nusea
c
      nu = nu / 100000.
      nusea = nusea / 100000.
c
c     Transform speeds from knots to ft/sec
c
      VCR = 1.6878 * VCRknot
      V = 1.6878 * Vknot
      VS = 1.6878 * VSknot
c
```

```
c       Transform rpm into rps
c
        n = nrpm / 60.
c
c       Transform torque from in-lb to ft-lb
c
        Q = Qinlb / 12.
c
c       Transform input percent uncertainties
c
        Uro = 0.01 * Uro
        Unu = 0.01 * Unu
c
        UL = 0.01 * UL
        US = 0.01 * US
        UD = 0.01 * UD
c
        URTCR = 0.01 * URTCR
        UV = 0.01 * UV
        URT = 0.01 * URT
        UDelR = 0.01 * UDelR
c
        Un = 0.01 * Un
        UT = 0.01 * UT
        UQ = 0.01 * UQ
c
        Uros = 0.01 * Uros
        Unus = 0.01 * Unus
c
        ULS = 0.01 * ULS
        USS = 0.01 * USS
        UDS = 0.01 * UDS
c
        UVfsm = 0.01 * UVfsm
        UNfsm = 0.01 * UNfsm
        UTfsm = 0.01 * UTfsm
        UQfsm = 0.01 * UQfsm
        UPfsm = 0.01 * UPfsm
c
c       MODEL-SCALE VARIABLES : RESISTANCE TESTS
c
c       Compute CTCR , CFCR & CR
c
        CTCR = 2. * RTCR / ( ro * S * VCR * VCR )
        CFCR = 0.075 / ( LOG10( VCR * L / nu ) - 2. )**2
        CR = CTCR - CFCR
```

```
c
c      MODEL-SCALE VARIABLES : PROPULSION TESTS
c
c      Compute Ri , CT & CF
c
       Ri = RT - DelR
       CT = 2. * Ri / ( ro * S * V * V )
       CF = 0.075 / ( LOG10( V * L / nu ) - 2. )**2
c
c      Compute JV , td=1-t & eta=etaD
c
       JV = V / ( n * D )
       td = Ri / T
       eta = V * Ri / ( 6.2831853 * n * Q )
c
c      PRELIMINARY CALCULATIONS FOR MODEL-SCALE UNCERTAINTIES
c
       Uro2 = Uro * Uro
       Unu2 = Unu * Unu
c
       UL2 = UL * UL
       US2 = US * US
       UD2 = UD * UD
c
       URTCR2 = URTCR * URTCR
       UV2 = UV * UV
c
       URi = ( URT * RT )**2 + ( UDelR * DelR )**2
       URi = SQRT( URi ) / Ri
       URi2 = URi * URi
c
       Un2 = Un * Un
       UT2 = UT * UT
       UQ2 = UQ * UQ
c
c      MODEL-SCALE UNCERTAINTIES : RESISTANCE TESTS
c
c      Compute dCTCR / CTCR
c
       UCTCR2 = URTCR2 + Uro2 + US2 + 4. * UV2
       UCTCR = 100. * SQRT( UCTCR2 )
c
c      Compute dCFCR / CFCR
c
       UCFCR2 = 10. * CFCR * ( UV2 + UL2 + Unu2 )
       UCFCR = 100. * SQRT( UCFCR2 )
```

```
c
c       Compute dCR^2 & dCR / CR
c
        dCR2 = UV2 * ( 2. * CTCR - CFCR * SQRT( 10. * CFCR ) )**2
        dCR2 = dCR2 + ( URTCR2 + Uro2 + US2 ) * CTCR**2
        dCR2 = dCR2 + ( UL2 + Unu2 ) * 10. * CFCR**3
        UCR = 100. * SQRT( dCR2 ) / CR
c
c       MODEL-SCALE UNCERTAINTIES : PROPULSION TESTS
c
c       Compute dCT / CT
c
        UCT2 = URi2 + Uro2 + US2 + 4. * UV2
        UCT = 100. * SQRT( UCT2 )
c
c       Compute dCF / CF
c
        UCF2 = 10. * CF * ( UV2 + UL2 + Unu2 )
        UCF = 100. * SQRT( UCF2 )
c
c       Compute dJV / JV , dtd / td & deta / eta
c
        UJV2 = UV2 + Un2 + UD2
        Utd2 = URi2 + UT2
        Ueta2 = UV2 +  URi2 + Un2 + UQ2
c
        UJV = 100. * SQRT( UJV2 )
        Utd = 100. * SQRT( Utd2 )
        Ueta = 100. * SQRT( Ueta2 )
c
c       PRELIMINARY CALCULATIONS FOR FULL-SCALE UNCERTAINTIES
c
c       Compute CFS & CTS
c
        CFS = 0.075 / ( LOG10( VS * LS / nusea ) - 2. )**2
        CTS = CFS + CR + CA
c
c       Compute (drhosea/rhosea)^2+(dSS/SS)^2 & (dJV/JV)^2+(dDS/DS)^2
c
        UroS2 = Uros**2 + USS**2
        UJD2 = UJV2 + UDS**2
c
c       Compute UCLnu2 & Gamma
c
        cofCFS = 10. * CFS**3
        UCLnu2 = ( dCR2 + dCA**2 ) / cofCFS + ULS**2 + Unus**2
```

```
      cofCFS = SQRT( cofCFS )
      Gamma = cofCFS / CTS
c
c     Compute sigmaJ , sigmat & sigmeta
c
      sigmaJ = cofCFS * JVCT / JV
      sigmat = cofCFS * tdCT / td
      sigmeta = cofCFS * etaCT / eta
c
c     Compute squares of full-scale measurement uncertainties
c
      UVfsm2 = UVfsm * UVfsm
      UNfsm2 = UNfsm * UNfsm
      UTfsm2 = UTfsm * UTfsm
      UQfsm2 = UQfsm * UQfsm
      UPfsm2 = UPfsm * UPfsm
c
c     FULL-SCALE UNCERTAINTIES @ a GIVEN SPEED
c
      UN2V = UVfsm2 * ( 1. + sigmaJ )**2 + UCLnu2 * sigmaJ**2
      UN2V = UN2V + UJD2 + UNfsm2
c
      UT2V = UVfsm2 * ( 2. - Gamma + sigmat )**2
      UT2V = UT2V + UCLnu2 * ( Gamma - sigmat )**2
      UT2V = UT2V + UroS2 + Utd2 + UTfsm2
c
      UQ2V = UVfsm2 * ( 2. - Gamma + sigmeta - sigmaJ )**2
      UQ2V = UQ2V + UCLnu2 * ( Gamma - sigmeta + sigmaJ )**2
      UQ2V = UQ2V + UroS2 + Ueta2 + UJD2 + UQfsm2
c
      UP2V = UVfsm2 * ( 3. - Gamma + sigmeta )**2
      UP2V = UP2V + UCLnu2 * ( Gamma - sigmeta )**2
      UP2V = UP2V + UroS2 + Ueta2 + UPfsm2
c
      UE2V = UVfsm2 * ( 3. - Gamma )**2 + UCLnu2 * Gamma**2 + UroS2
c
      UVV = 100. * UVfsm
      UNV = 100. * SQRT( UN2V )
      UTV = 100. * SQRT( UT2V )
      UQV = 100. * SQRT( UQ2V )
      UPV = 100. * SQRT( UP2V )
      UEV = 100. * SQRT( UE2V )
      UAV = 20. * SQRT( UVfsm2 + UN2V + UT2V + UQ2V + UP2V )
c
c     FULL-SCALE UNCERTAINTIES @ a GIVEN rpm
c
```

```
      UV2N = UNfsm2 + UCLnu2 * sigmaJ**2 + UJD2
      UV2N = UV2N / ( 1. + sigmaJ )**2 + UVfsm2
c
      UT2N = ( UNfsm2 + UJD2 ) * ( 2. - Gamma + sigmat )**2
      UT2N = UT2N + UCLnu2 * ( Gamma - sigmat + 2. * sigmaJ )**2
      UT2N = UT2N / ( 1. + sigmaJ )**2 + UroS2 + Utd2 + UTfsm2
c
      UQ2N = UNfsm2 * ( 2. - Gamma + sigmeta - sigmaJ )**2
      UQ2N = UQ2N + UCLnu2 * ( Gamma - sigmeta + 3. * sigmaJ )**2
      UQ2N = UQ2N + UJD2 * ( 3. - Gamma + sigmeta )**2
      UQ2N = UQ2N / ( 1. + sigmaJ )**2 + UroS2 + Ueta2 + UQfsm2
c
      UP2N = ( UNfsm2 + UJD2 ) * ( 3. - Gamma + sigmeta )**2
      UP2N = UP2N + UCLnu2 * ( Gamma - sigmeta + 3. * sigmaJ )**2
      UP2N = UP2N / ( 1. + sigmaJ )**2 + UroS2 + Ueta2 + UPfsm2
c
      UE2N =  ( UNfsm2 + UJD2 ) * ( 3. - Gamma )**2
      UE2N = UE2N + UCLnu2 * ( Gamma + 3. * sigmaJ )**2
      UE2N = UE2N / ( 1. + sigmaJ )**2 + UroS2
c
      UNN = 100. * UNfsm
      UVN = 100. * SQRT( UV2N )
      UTN = 100. * SQRT( UT2N )
      UQN = 100. * SQRT( UQ2N )
      UPN = 100. * SQRT( UP2N )
      UEN = 100. * SQRT( UE2N )
      UAN = 20. * SQRT( UV2N + UNfsm2 + UT2N + UQ2N + UP2N )
c
c     FULL-SCALE UNCERTAINTIES @ a GIVEN THRUST
c
      UV2T = UTfsm2 + UCLnu2 * ( Gamma - sigmat )**2 + UroS2 + Utd2
      UV2T = UV2T / ( 2. - Gamma + sigmat )**2 + UVfsm2
c
      UN2T = ( UTfsm2 + UroS2 + Utd2 ) * ( 1. + sigmaJ )**2
      UN2T = UN2T + UCLnu2 * ( Gamma - sigmat + 2. * sigmaJ )**2
      UN2T = UN2T / ( 2. - Gamma + sigmat )**2 + UJD2 + UNfsm2
c
      UQ2T = ( UTfsm2 + Utd2 ) * ( 2. - Gamma + sigmeta - sigmaJ )**2
      UQ2T = UQ2T + ( 4. * UCLnu2 + UroS2 ) * ( sigmat - sigmeta + sigmaJ )**2
      UQ2T = UQ2T / ( 2. - Gamma + sigmat )**2 + UJD2 + Ueta2 + UQfsm2
c
      UP2T = ( UTfsm2 + Utd2 ) * ( 3. - Gamma + sigmeta )**2
      UP2T = UP2T + UCLnu2 * ( Gamma + 2. * sigmeta - 3. * sigmat )**2
      UP2T = UP2T + UroS2 * ( 1. + sigmeta - sigmat )**2
      UP2T = UP2T / ( 2. - Gamma + sigmat )**2 + Ueta2 + UPfsm2
c
```

```
      UE2T = ( UTfsm2 + Utd2 ) * ( 3. - Gamma )**2
      UE2T = UE2T + UCLnu2 * ( Gamma - 3. * sigmat )**2
      UE2T = UE2T + UroS2 * ( 1.  - sigmat )**2
      UE2T = UE2T / ( 2. - Gamma + sigmat )**2
c
      UTT = 100. * UTfsm
      UVT = 100. * SQRT( UV2T )
      UNT = 100. * SQRT( UN2T )
      UQT = 100. * SQRT( UQ2T )
      UPT = 100. * SQRT( UP2T )
      UET = 100. * SQRT( UE2T )
      UAT = 20. * SQRT( UV2T + UN2T + UTfsm2 + UQ2T + UP2T )
c
c     FULL-SCALE UNCERTAINTIES @ a GIVEN TORQUE
c
      UV2Q = UQfsm2 + UCLnu2 * ( Gamma - sigmeta + sigmaJ )**2
      UV2Q = UV2Q + UroS2 + Ueta2 + UJD2
      UV2Q = UV2Q / ( 2. - Gamma + sigmeta - sigmaJ )**2 + UVfsm2
c
      UN2Q = ( UQfsm2 + UroS2 + Ueta2 ) * ( 1. + sigmaJ )**2
      UN2Q = UN2Q + UCLnu2 * ( Gamma - sigmeta + 3. * sigmaJ )**2
      UN2Q = UN2Q + UJD2 * ( 3. - Gamma + sigmeta )**2
      UN2Q = UN2Q / ( 2. - Gamma + sigmeta - sigmaJ )**2 + UNfsm2
c
      UT2Q = ( UQfsm2 + Ueta2 + UJD2 ) * ( 2. - Gamma + sigmat )**2
      UT2Q = UT2Q + ( 4. * UCLnu2 + UroS2 ) * ( sigmat - sigmeta + sigmaJ )**2
      UT2Q = UT2Q / ( 2. - Gamma + sigmeta - sigmaJ )**2 + Utd2 + UTfsm2
c
      UP2Q = ( UQfsm2 + UJD2 ) * ( 3. - Gamma + sigmeta )**2
      UP2Q = UP2Q + UCLnu2 * ( Gamma - sigmeta + 3. * sigmaJ )**2
      UP2Q = UP2Q + ( UroS2 + Ueta2 ) * ( 1. + sigmaJ )**2
      UP2Q = UP2Q / ( 2. - Gamma + sigmeta - sigmaJ )**2 + UPfsm2
c
      UE2Q = ( UQfsm2 + UJD2 ) * ( 3. - Gamma )**2
      UE2Q = UE2Q + UCLnu2 * ( Gamma + 3. * sigmaJ )**2
      UE2Q = UE2Q + UroS2 * ( 1. + sigmaJ )**2
      UE2Q = UE2Q / ( 2. - Gamma - sigmaJ )**2
c
      UQQ = 100. * UQfsm
      UVQ = 100. * SQRT( UV2Q )
      UNQ = 100. * SQRT( UN2Q )
      UTQ = 100. * SQRT( UT2Q )
      UPQ = 100. * SQRT( UP2Q )
      UEQ = 100. * SQRT( UE2Q )
      UAQ = 20. * SQRT( UV2Q + UN2Q + UT2Q + UQfsm2 + UP2Q )
c
```

```
c       FULL-SCALE UNCERTAINTIES @ a GIVEN SHAFT HORSEPOWER
c
        UV2P = UPfsm2 + UCLnu2 * (Gamma-sigmeta)**2 + UroS2 + Ueta2
        UV2P = UV2P / ( 3. - Gamma + sigmeta )**2 + UVfsm2
c
        UN2P = ( UPfsm2 + UroS2 + Ueta2 ) * ( 1. + sigmaJ )**2
        UN2P = UN2P + UCLnu2 * ( Gamma - sigmeta + 3. * sigmaJ )**2
        UN2P = UN2P / ( 3. - Gamma + sigmeta )**2 + UJD2 + UNfsm2
c
        UT2P = ( UPfsm2 + Ueta2 ) * ( 2. - Gamma + sigmat )**2
        UT2P = UT2P + UCLnu2 * (Gamma+2.*sigmeta-3.*sigmat)**2
        UT2P = UT2P + UroS2 * ( 1. + sigmeta - sigmat )**2
        UT2P = UT2P / ( 3. - Gamma + sigmeta )**2 + Utd2 + UTfsm2
c
        UQ2P = UPfsm2 * ( 2. - Gamma + sigmeta - sigmaJ )**2
        UQ2P = UQ2P + UCLnu2 * ( Gamma - sigmeta + 3. * sigmaJ )**2
        UQ2P = UQ2P + ( UroS2 + Ueta2 ) * ( 1. + sigmaJ )**2
        UQ2P = UQ2P / ( 3. - Gamma + sigmeta )**2 + UJD2 + UQfsm2
c
        UE2P = ( UPfsm2 + Ueta2 ) * ( 3. - Gamma )**2
        UE2P = UE2P + ( 9. * UCLnu2 + UroS2 ) * sigmeta**2
        UE2P = UE2P / ( 3. - Gamma + sigmeta )**2
c
        UPP = 100. * UPfsm
        UVP = 100. * SQRT( UV2P )
        UNP = 100. * SQRT( UN2P )
        UTP = 100. * SQRT( UT2P )
        UQP = 100. * SQRT( UQ2P )
        UEP = 100. * SQRT( UE2P )
        UAP = 20. * SQRT( UV2P + UN2P + UT2P + UQ2P + UPfsm2 )
c
c       WRITE INPUT VARIABLES & OUTPUT RESULTS
c
c       Express relative uncertainties in percent
c
        Uro = 100. * Uro
        Unu = 100. * Unu
c
        UL = 100. * UL
        US = 100. * US
        UD = 100. * UD
c
        URTCR = 100. * URTCR
        UV = 100. * UV
        URT = 100. * URT
        UDelR = 100. * UDelR
```

```
c
      Un = 100. * Un
      UT = 100. * UT
      UQ = 100. * UQ
c
      Uros = 100. * Uros
      Unus = 100. * Unus
c
      ULS = 100. * ULS
      USS = 100. * USS
      UDS = 100. * UDS
c
      UVfsm = 100. * UVfsm
      UNfsm = 100. * UNfsm
      UTfsm = 100. * UTfsm
      UQfsm = 100. * UQfsm
      UPfsm = 100. * UPfsm
c
      UCA = 100. * dCA / CA
c
      open(12,file='UA3.out',status='new')
c
      write(12,*) TTxp
      write(12,*) date
      write(12,*) model
      write(12,*) prop
      write(12,*) EHPxp
      write(12,*) SHPxp
      write(12,*) comment
c
      write(12,*)
      write(12,*) ' INPUT VARIABLES'
      write(12,*)
c
      write(12,*)
      write(12,*) ' TANK-WATER PROPERTIES'
      write(12,*)
      write(12,101) ro
      write(12,102) nu
      write(12,103) Uro
      write(12,104) Unu
c
      write(12,*)
      write(12,*) ' MODEL GEOMETRY'
      write(12,*)
      write(12,105) L
```

```
      write(12,106) S
      write(12,107) D
      write(12,108) UL
      write(12,109) US
      write(12,110) UD
c
      write(12,*)
      write(12,*) ' MODEL-SCALE VARIABLES : RESISTANCE TESTS'
      write(12,*)
      write(12,111) VCRknot
      write(12,112) RTCR
      write(12,113) URTCR
c
      write(12,*)
      write(12,*) ' MODEL-SCALE VARIABLES : PROPULSION TESTS'
      write(12,*)
      write(12,114) Vknot
      write(12,115) RT
      write(12,116) DelR
      write(12,117) nrpm
      write(12,118) T
      write(12,119) Qinlb
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES OF MODEL-SCALE MEASUREMENTS'
      write(12,*)
      write(12,120) UV
      write(12,121) URT
      write(12,122) UDelR
      write(12,123) Un
      write(12,124) UT
      write(12,125) UQ
c
      write(12,*)
      write(12,*) ' OTHER MODEL-SCALE VARIABLES'
      write(12,*)
      write(12,126) JVCT
      write(12,127) tdCT
      write(12,128) etaCT
c
      write(12,*)
      write(12,*) ' SEA-WATER PROPERTIES'
      write(12,*)
      write(12,151) nusea
      write(12,152) Uros
      write(12,153) Unus
```

```
c
      write(12,*)
      write(12,*) ' FULL-SCALE SHIP'
      write(12,*)
      write(12,154) LS
      write(12,155) VSknot
      write(12,156) ULS
      write(12,157) USS
      write(12,158) UDS
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES OF FULL-SCALE MEASUREMENTS'
      write(12,*)
      write(12,159) UVfsm
      write(12,160) UNfsm
      write(12,161) UTfsm
      write(12,162) UQfsm
      write(12,163) UPfsm
c
      write(12,*)
      write(12,*) ' SCALING ALLOWANCE'
      write(12,*)
      write(12,171) CA
      write(12,172) dCA
c
      write(12,*)
      write(12,*)
      write(12,*) ' OUTPUT VARIABLES'
      write(12,*)
c
      write(12,*)
      write(12,*) ' MODEL-SCALE VARIABLES : RESISTANCE TESTS'
      write(12,*)
      write(12,201) CTCR
      write(12,202) CFCR
      write(12,203) CR
c
      write(12,*)
      write(12,*) ' MODEL-SCALE VARIABLES : PROPULSION TESTS'
      write(12,*)
      write(12,204) CT
      write(12,205) CF
      write(12,206) CR
      write(12,*)
      write(12,207) JV
      write(12,208) td
```

```
      write(12,209) eta
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES OF MODEL-SCALE VARIABLES :
      RESISTANCE TESTS'
      write(12,*)
      write(12,210) UCTCR
      write(12,211) UCFCR
      write(12,212) UCR
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES OF MODEL-SCALE VARIABLES :
      PROPULSION TESTS'
      write(12,*)
      write(12,213) UCT
      write(12,214) UCF
      write(12,215) UCR
      write(12,216) UCA
      write(12,*)
      write(12,217) UJV
      write(12,218) Utd
      write(12,219) Ueta
c
      write(12,*)
      write(12,*) ' FULL-SCALE VARIABLES'
      write(12,*)
      write(12,220) CTS
      write(12,221) CFS
      write(12,222) CR
      write(12,223) CA
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
      SPEED'
      write(12,*)
      write(12,311) UVV
      write(12,312) UNV
      write(12,313) UTV
      write(12,314) UQV
      write(12,315) UPV
      write(12,316) UEV
      write(12,317) UAV
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
      rpm'
```

```
      write(12,*)
      write(12,321) UVN
      write(12,322) UNN
      write(12,323) UTN
      write(12,324) UQN
      write(12,325) UPN
      write(12,326) UEN
      write(12,327) UAN
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
      THRUST'
      write(12,*)
      write(12,331) UVT
      write(12,332) UNT
      write(12,333) UTT
      write(12,334) UQT
      write(12,335) UPT
      write(12,336) UET
      write(12,337) UAT
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
      TORQUE'
      write(12,*)
      write(12,341) UVQ
      write(12,342) UNQ
      write(12,343) UTQ
      write(12,344) UQQ
      write(12,345) UPQ
      write(12,346) UEQ
      write(12,347) UAQ
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
      SHP'
      write(12,*)
      write(12,351) UVP
      write(12,352) UNP
      write(12,353) UTP
      write(12,354) UQP
      write(12,355) UPP
      write(12,356) UEP
      write(12,357) UAP
c
      close(12,status='keep')
```

```
c
c     FORMATS
c
101  format(' water density (slug/ft**3) :              ',F11.3)
102  format(' kinematic viscosity coefficient (ft**2/sec) : ',E11.4)
103  format(' percent uncertainty of density :  ',F8.2)
104  format(' percent uncertainty of viscosity : ',F8.2)
c
105  format(' length of model (ft) :       ',F8.3)
106  format(' wetted area (ft**2) :        ',F8.3)
107  format(' diameter of propeller (ft) :  ',F8.4)
108  format(' percent uncertainty of length :         ',F8.2)
109  format(' percent uncertainty of wetted surface : ',F8.2)
110  format(' percent uncertainty of prop diameter :  ',F8.2)
c
111  format(' carriage speed (knots) :          ',F8.2)
112  format(' drag (lbs) :                        ',F8.2)
113  format(' percent uncertainty of drag :       ',F8.2)
c
114  format(' carriage speed (knots) :   ',F8.2)
115  format(' drag RT (lbs) :           ',F8.2)
116  format(' drag DeltaR (lbs) :       ',F8.2)
117  format(' propeller rpm :           ',F8.2)
118  format(' propeller thrust (lbs) :   ',F8.2)
119  format(' propeller torque (in-lbs) : ',F8.2)
c
120  format(' percent uncertainty of model speed :   ',F8.2)
121  format(' percent uncertainty of drag RT :       ',F8.2)
122  format(' percent uncertainty of drag DeltaR :   ',F8.2)
123  format(' percent uncertainty of propeller rpm :  ',F8.2)
124  format(' percent uncertainty of prop thrust :    ',F8.2)
125  format(' percent uncertainty of prop torque :    ',F8.2)
c
126  format(' slope d JV / d CT :    ',F9.3)
127  format(' slope d (1-t) / d CT : ',F9.3)
128  format(' slope d etaD /  d CT : ',F9.3)
c
151  format(' kinematic viscosity coefficient (ft**2/sec) : ',E11.4)
152  format(' percent uncertainty of density :  ',F8.2)
153  format(' percent uncertainty of viscosity : ',F8.2)
c
154  format(' ship length (ft) :            ',F8.2)
155  format(' ship speed (knots) :        ',F11.1)
c
156  format(' percent uncertainty of ship length :    ',F8.2)
157  format(' percent uncertainty of wetted surface : ',F8.2)
```

```
158   format(' percent uncertainty of prop diameter :  ',F8.2)
c
159   format(' percent uncertainty of ship speed :   ',F8.2)
160   format(' percent uncertainty of prop rpm :     ',F8.2)
161   format(' percent uncertainty of prop thrust :  ',F8.2)
162   format(' percent uncertainty of prop torque :  ',F8.2)
163   format(' percent uncertainty of SHP :          ',F8.2)
c
171   format(' correlation allowance :      ',F11.5)
172   format(' uncertainty of allowance :   ',F11.5)
c
201   format(' total resistance coefficient CT :        ',F10.5)
202   format(' friction resistance coefficient CF :     ',F10.5)
203   format(' residuary resistance coefficient CR :    ',F10.5)
c
204   format(' total resistance coefficient CT :        ',F10.5)
205   format(' friction resistance coefficient CF :     ',F10.5)
206   format(' residuary resistance coefficient CR :    ',F10.5)
c
207   format(' advance ratio JV :            ',F8.2)
208   format(' thrust-deduction factor 1-t : ',F8.2)
209   format(' propulsive efficiency etaD :  ',F8.2)
c
210   format(' percent uncertainty of CT : ',F8.2)
211   format(' percent uncertainty of CF : ',F8.2)
212   format(' percent uncertainty of CR : ',F8.2)
c
213   format(' percent uncertainty of CT : ',F8.2)
214   format(' percent uncertainty of CF : ',F8.2)
215   format(' percent uncertainty of CR : ',F8.2)
216   format(' percent uncertainty of CA : ',F8.2)
c
217   format(' percent uncertainty of JV :   ',F8.2)
218   format(' percent uncertainty of 1-t :  ',F8.2)
219   format(' percent uncertainty of etaD : ',F8.2)
c
220   format(' total resistance coefficient CT :        ',F10.5)
221   format(' friction resistance coefficient CF :     ',F10.5)
222   format(' residuary resistance coefficient CR :    ',F10.5)
223   format(' correlation allowance coefficient CA : ',F10.5)
c
311   format(' percent uncertainty of ship speed :   ',F8.2)
312   format(' percent uncertainty of prop rpm :     ',F8.2)
313   format(' percent uncertainty of prop thrust : ',F8.2)
314   format(' percent uncertainty of prop torque : ',F8.2)
315   format(' percent uncertainty of SHP :          ',F8.2)
```

```
316  format(' percent uncertainty of EHP :         ',F8.2)
317  format(' percent overall uncertainty :        ',F8.2)
c
321  format(' percent uncertainty of ship speed :  ',F8.2)
322  format(' percent uncertainty of prop rpm :    ',F8.2)
323  format(' percent uncertainty of prop thrust : ',F8.2)
324  format(' percent uncertainty of prop torque : ',F8.2)
325  format(' percent uncertainty of SHP :         ',F8.2)
326  format(' percent uncertainty of EHP :         ',F8.2)
327  format(' percent overall uncertainty :        ',F8.2)
c
331  format(' percent uncertainty of ship speed :  ',F8.2)
332  format(' percent uncertainty of prop rpm :    ',F8.2)
333  format(' percent uncertainty of prop thrust : ',F8.2)
334  format(' percent uncertainty of prop torque : ',F8.2)
335  format(' percent uncertainty of SHP :         ',F8.2)
336  format(' percent uncertainty of EHP :         ',F8.2)
337  format(' percent overall uncertainty :        ',F8.2)
c
341  format(' percent uncertainty of ship speed :  ',F8.2)
342  format(' percent uncertainty of prop rpm :    ',F8.2)
343  format(' percent uncertainty of prop thrust : ',F8.2)
344  format(' percent uncertainty of prop torque : ',F8.2)
345  format(' percent uncertainty of SHP :         ',F8.2)
346  format(' percent uncertainty of EHP :         ',F8.2)
347  format(' percent overall uncertainty :        ',F8.2)
c
351  format(' percent uncertainty of ship speed :  ',F8.2)
352  format(' percent uncertainty of prop rpm :    ',F8.2)
353  format(' percent uncertainty of prop thrust : ',F8.2)
354  format(' percent uncertainty of prop torque : ',F8.2)
355  format(' percent uncertainty of SHP :         ',F8.2)
356  format(' percent uncertainty of EHP :         ',F8.2)
357  format(' percent overall uncertainty :        ',F8.2)
c
     stop
c
     end
```

EXAMPLE INPUT FILE

```
' TOW-TANK EXP '
' DATE: XXXX '
' MODEL No. XXXX '
' PROPELLER No. XXXX '
' EHP EXPERIMENT No. XXXX '
' SHP EXPERIMENT No. XXXX '
' COMMENTS: CASE MFC '

MODEL-SCALE VARIABLES AND UNCERTAINTIES

Tank-water density (rho) and kinematic viscosity (nu)
rho (slug/ft**3)      nu X 10**5 (ft**2/sec)
1.9367 ,              1.084

Percent relative uncertainties of rho & nu
density     kinematic viscosity
0.07 ,          2.1

Model geometry
length (ft)   area (ft**2)   prop diameter (ft)
22.697 ,      138.179 ,        0.9986

Percent relative uncertainties of model geometry
length     area     prop diameter
0.14 ,     0.71 ,   0.071

              RESISTANCE (EHP) TESTS

speed (knots)   drag (lbs)
6.0 ,            46.66

Percent relative uncertainty of drag
1.7

              PROPULSION TESTS

speed (knots)   RT (lbs)   DeltaR
18.0 ,          392.64 ,    70.1

rpm      thrust (lbs)    torque (in-lbs)
923.4 ,  551.0 ,         1501.0

Percent relative uncertainties
speed   RT     DeltaR   rpm     thrust   torque
0.21 ,  1.7 ,  1.7 ,    0.42 ,  0.71 ,   0.71
```

Other model variables : slopes of 1-t , JV & etaD versus CT

dJV/dCT	d(1-t)/dCT	detaD/dCT
-0.249 ,	0.067 ,	-0.015

FULL-SCALE VARIABLES AND UNCERTAINTIES

Sea-water kinematic viscosity
nu X 10**5 (ft**2/sec)
1.282

Percent relative uncertainties of sea-water properties

density	kinematic viscosity
1.0 ,	2.0

Full-scale variables

ship length (ft)	ship speed (knots)
380.0 ,	25.0

Percent relative uncertainties of full-scale geometry

length	area	prop diameter
0.5 ,	1.0 ,	0.1

Percent relative uncertainties of full-scale measurements

speed	rpm	thrust	torque	SHP
0.6 ,	0.4 ,	3.0 ,	0.9 ,	0.9

SCALING ALLOWANCE

CA	dCA
0.0005 ,	0.0001

EXAMPLE OUTPUT FILE

TOW-TANK EXP
DATE: XXXX
MODEL No. XXXX
PROPELLER No. XXXX
EHP EXPERIMENT No. XXXX
SHP EXPERIMENT No. XXXX
COMMENTS: CASE MFC

INPUT VARIABLES

TANK-WATER PROPERTIES

water density (slug/ft**3) : 1.937
kinematic viscosity coefficient (ft**2/sec) : 0.1084E-04
percent uncertainty of density : 0.07
percent uncertainty of viscosity : 2.10

MODEL GEOMETRY

length of model (ft) : 22.697
wetted area (ft**2) : 138.179
diameter of propeller (ft) : 0.9986
percent uncertainty of length : 0.14
percent uncertainty of wetted surface : 0.71
percent uncertainty of prop diameter : 0.07

MODEL-SCALE VARIABLES : RESISTANCE TESTS

carriage speed (knots) : 6.00
drag (lbs) : 46.66
percent uncertainty of drag : 1.70

MODEL-SCALE VARIABLES : PROPULSION TESTS

carriage speed (knots) : 18.00
drag RT (lbs) : 392.64
drag DeltaR (lbs) : 70.10
propeller rpm : 923.40
propeller thrust (lbs) : 551.00
propeller torque (in-lbs) : 1501.00

UNCERTAINTIES OF MODEL-SCALE MEASUREMENTS

percent uncertainty of model speed : 0.21

percent uncertainty of drag RT : 1.70
percent uncertainty of drag DeltaR : 1.70
percent uncertainty of propeller rpm : 0.42
percent uncertainty of prop thrust : 0.71
percent uncertainty of prop torque : 0.71

OTHER MODEL-SCALE VARIABLES

slope d JV / d CT : -0.249
slope d (1-t) / d CT : 0.067
slope d etaD / d CT : -0.015

SEA-WATER PROPERTIES

kinematic viscosity coefficient (ft**2/sec) : 0.1282E-04
percent uncertainty of density : 1.00
percent uncertainty of viscosity : 2.00

FULL-SCALE SHIP

ship length (ft) : 380.00
ship speed (knots) : 25.0
percent uncertainty of ship length : 0.50
percent uncertainty of wetted surface : 1.00
percent uncertainty of prop diameter : 0.10

UNCERTAINTIES OF FULL-SCALE MEASUREMENTS

percent uncertainty of ship speed : 0.60
percent uncertainty of prop rpm : 0.40
percent uncertainty of prop thrust : 3.00
percent uncertainty of prop torque : 0.90
percent uncertainty of SHP : 0.90

SCALING ALLOWANCE

correlation allowance : 0.00050
uncertainty of allowance : 0.00010

OUTPUT VARIABLES

MODEL-SCALE VARIABLES : RESISTANCE TESTS

total resistance coefficient CT : 0.00340
friction resistance coefficient CF : 0.00264

residuary resistance coefficient CR : 0.00075

MODEL-SCALE VARIABLES : PROPULSION TESTS

total resistance coefficient CT : 0.00261
friction resistance coefficient CF : 0.00223
residuary resistance coefficient CR : 0.00075

advance ratio JV : 1.98
thrust-deduction factor 1-t : 0.59
propulsive efficiency etaD : 0.81

UNCERTAINTIES OF MODEL-SCALE VARIABLES : RESISTANCE TESTS

percent uncertainty of CT : 1.89
percent uncertainty of CF : 0.34
percent uncertainty of CR : 8.58

UNCERTAINTIES OF MODEL-SCALE VARIABLES : PROPULSION TESTS

percent uncertainty of CT : 2.26
percent uncertainty of CF : 0.32
percent uncertainty of CR : 8.58
percent uncertainty of CA : 20.00

percent uncertainty of JV : 0.47
percent uncertainty of 1-t : 2.22
percent uncertainty of etaD : 2.27

FULL-SCALE VARIABLES

total resistance coefficient CT : 0.00274
friction resistance coefficient CF : 0.00149
residuary resistance coefficient CR : 0.00075
correlation allowance coefficient CA : 0.00050

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN SPEED

percent uncertainty of ship speed : 0.60
percent uncertainty of prop rpm : 0.87
percent uncertainty of prop thrust : 6.01
percent uncertainty of prop torque : 5.33
percent uncertainty of SHP : 5.47
percent uncertainty of EHP : 4.90
percent overall uncertainty : 1.96

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN rpm

percent uncertainty of ship speed :	0.87
percent uncertainty of prop rpm :	0.40
percent uncertainty of prop thrust :	6.02
percent uncertainty of prop torque :	5.42
percent uncertainty of SHP :	5.50
percent uncertainty of EHP :	4.92
percent overall uncertainty :	1.97

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN THRUST

percent uncertainty of ship speed :	3.11
percent uncertainty of prop rpm :	3.11
percent uncertainty of prop thrust :	3.00
percent uncertainty of prop torque :	4.48
percent uncertainty of SHP :	6.60
percent uncertainty of EHP :	6.13
percent overall uncertainty :	1.92

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN TORQUE

percent uncertainty of ship speed :	2.76
percent uncertainty of prop rpm :	2.80
percent uncertainty of prop thrust :	4.48
percent uncertainty of prop torque :	0.90
percent uncertainty of SHP :	3.19
percent uncertainty of EHP :	2.82
percent overall uncertainty :	1.36

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN SHP

percent uncertainty of ship speed :	1.86
percent uncertainty of prop rpm :	1.87
percent uncertainty of prop thrust :	4.35
percent uncertainty of prop torque :	2.10
percent uncertainty of SHP :	0.90
percent uncertainty of EHP :	2.44
percent overall uncertainty :	1.12

APPENDIX D:
REPEATABILITY OF MODEL-SCALE MEASUREMENTS

The precision uncertainties associated with submarine model tow-tank testing are investigated by considering two complete tow-tank test series. These two test series are representative of the submarine model resistance and powering experimental evaluations currently being performed in the NSWCCD towing tank. The first test series was performed from 01/2/96 to 2/20/96. The second test series was performed from 5/19/97 to 06/20/97. The current model test speed range of 6-18 knots is represented in these tests, as well as the current data collection instrumentation and calibration techniques.

The precision uncertainties of the model measurements of speed, drag, rpm, thrust, and torque are evaluated two ways. First, the gage calibrations and instrumentation were analyzed for uncertainties. The drag, thrust, and torque gages are calibrated on site and the electronic instrumentation manufacturer specifications are examined. These precision uncertainties are generally very small. A better assessment of the model measurement precision uncertainties is obtained by analyzing the collected test data. This second way of evaluating the measurement precision uncertainties takes into account the whole data collection system, including the effects of changing model conditions during a test series, water flow variations, variation in force gages, instrumentation accuracy, carriage vibrations, and computer collection and recording of the collected model speed, model drag, shaft RPM, shaft thrust and shaft torque values. The methods used to determine the precision uncertainties of the model provide conservative uncertainty values for use in the global uncertainty analysis. The calibration and measurement precision uncertainties for the five main measured model quantities, i.e., model speed and drag, shaft RPM, thrust, and torque, are examined below.

Calibration of the drag, thrust, and torque gages is completed before each test series. These calibrations consist of determining a unit/volt factor which is used for converting from measured volts to physical units. The weights used for the calibration are calibrated every two years to a tolerance of 0.01% of the nominal weight by the State of Maryland Department of Agriculture Weights and Measures Section. The tolerances are given in Table 2 through 5 of the NIST Handbook 105-1 (Revised 1990), "Class F Tolerances for Field Standards Weights." The uncertainty of a single measurement within a calibration is calculated by first taking two times the standard deviation of the data spots within that calibration. The average of these standard deviations for all the calibrations is calculated next and represents the precision uncertainty of a single measurement in the test series. This also provides verification of the linearity of the calibration factor. The cal factor used for the test is determined by averaging the multiple number of calibrations for each gage. The precision error associated with determining the cal factor is given by two times the standard deviation of the set of averages of the calibrations. Figure D.1. presents calibration examples for drag, thrust, and torque. The instrumentation currently being used for the model test measurements is presented in Table D.1. The calibration precision uncertainty results are presented in Table D.2. and D.3. for two test series.

A typical resistance or powering experiment will consist of a minimum of approximately 20 data spots with each data spot consisting of the average value of 5 seconds of data collection at 400 samples/second for a total sample of 2000 for a set speed, drag, and RPM (for powering) condition.

The precision uncertainty for model speed is calculated using all the speed data from the tests within the two series. Two times the standard deviation of approximately 20 data spots for each test was calculated to determine the precision uncertainty for that particular test. The results are presented in Tables D.4. and D.5. Model speed collected for a typical experiment is presented in Figure D.2.

The precision uncertainty in model drag is calculated by using measured values of drag at the same nominal model speed. A correction is applied to the measured drag to reduce the effects of the speed variation on the measured drag uncertainty. The measured drag is multiplied by $(V_N)^2 / (V_M)^2$, where V_M = measured speed and V_N = nominal speed. EHP tests, before no-loads, and after no-loads are used as the source of the data. This drag data was taken throughout the test series and therefore represents a large data set for the uncertainty analysis. The no-loads are collected before and after most SHP tests to find the model drag and other forces. No-loads are also a check to ensure that test conditions have not changed. The precision uncertainties are presented in Tables D.6. and D.7. Model drag measurements for a complete test series are presented in Figure D.3.

The precision uncertainties for model thrust, torque, and RPM are determined differently from the model drag and speed uncertainties. Typical submarine powering experiments consist of varying the propeller rpm to produce different submarine loadings. The precision uncertainty for the shaft thrust, torque, and RPM has been estimated by determining the variation of the thrust, torque, and RPM data from a least squares curve fit through the data spots of a test. Each test contains about 20 data spots which comprise a range of thrust, torque and RPM versus total drag coefficient (C_T) values. The thrust, torque, and RPM are plotted against C_T and a second-order least squared curve is fit through each set of data. Twice the standard error estimate of the data set is calculated and taken to be the precision uncertainty for that test. Examples are shown in Figures D.4., D.5., and D.6. The results are presented in Tables D.8. and D.9.

The following table summarizes the precision uncertainties for tow-tank model testing.

U_P speed	U_P drag	U_P thrust	U_P torque	U_P rpm
0.15%	1.2%	0.5%	0.5%	0.3%

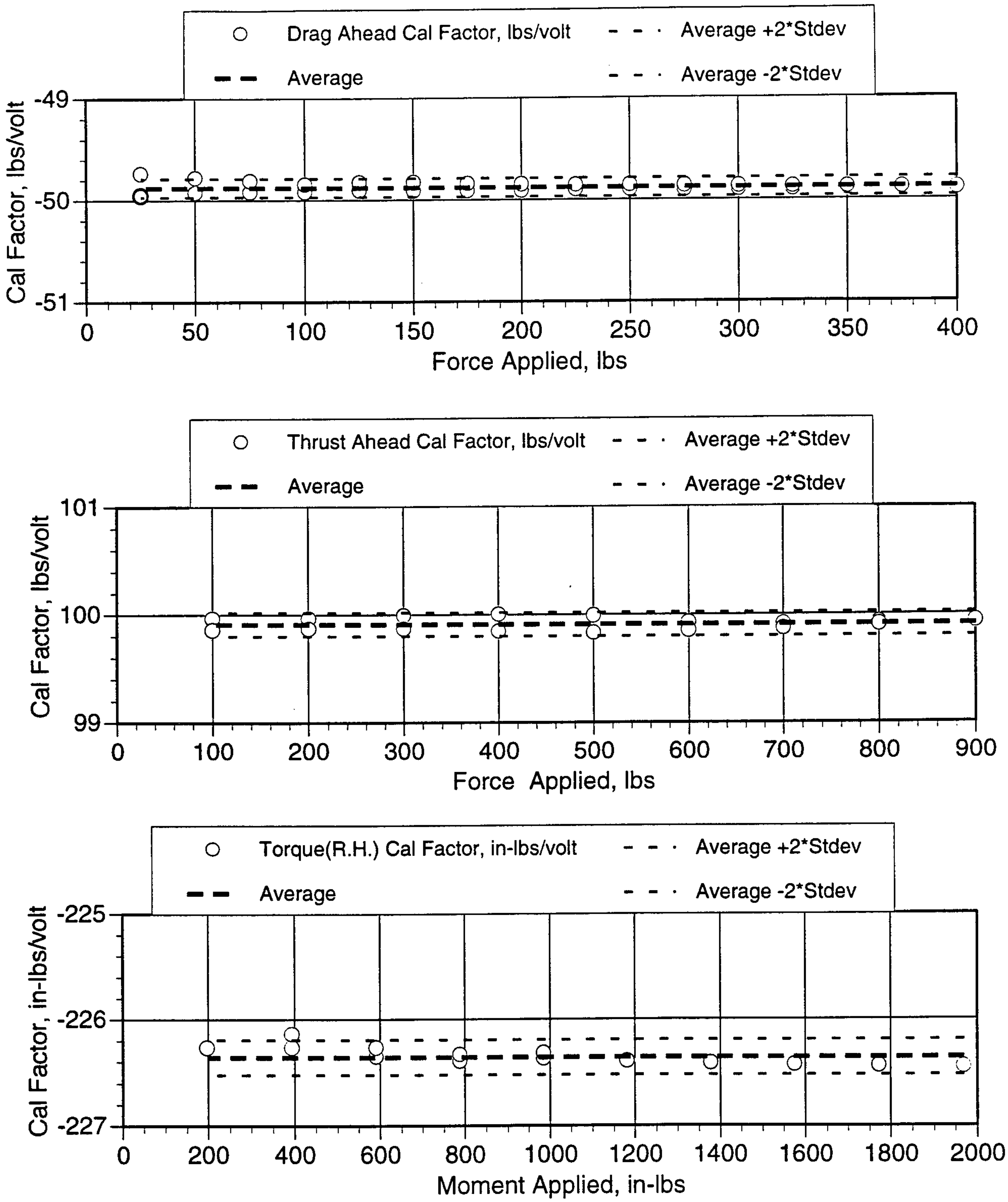

Fig. D.1. Examples of calibration measurements and uncertainty for model drag, thrust, and torque

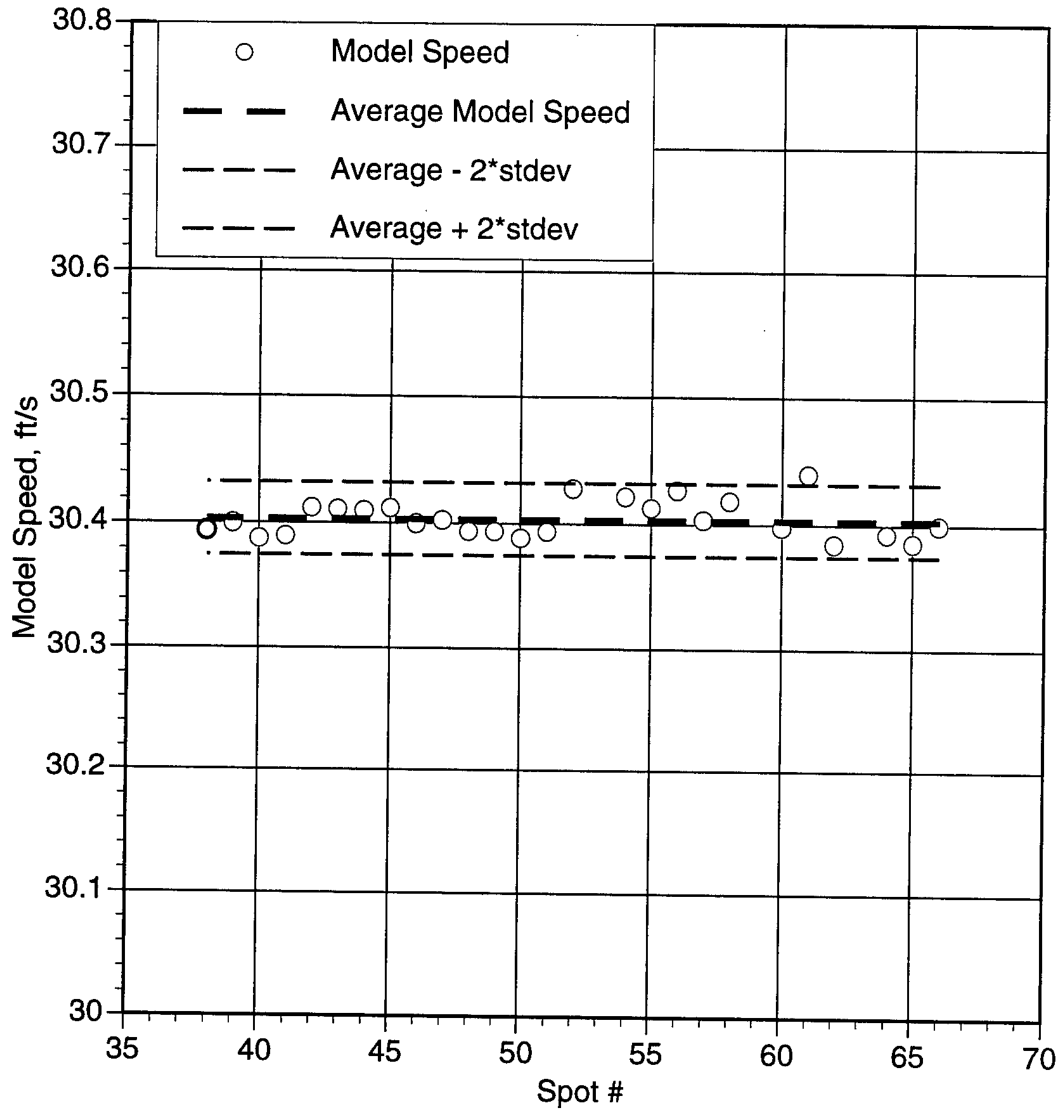

Fig. D.2. Example of model speed measurements and uncertainty for one experiment

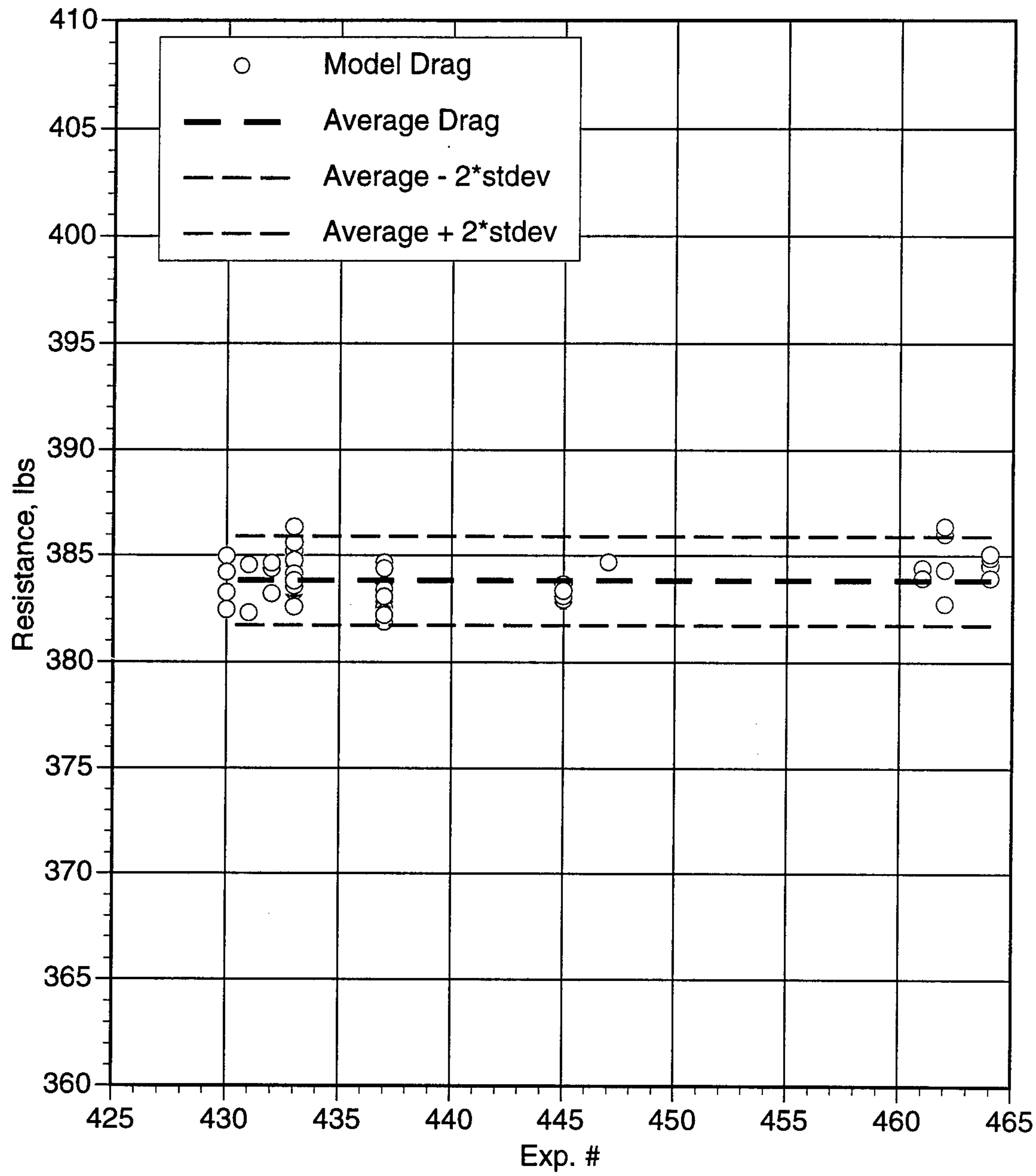

Fig. D.3. Example of model drag measurements and uncertainty for a complete test series

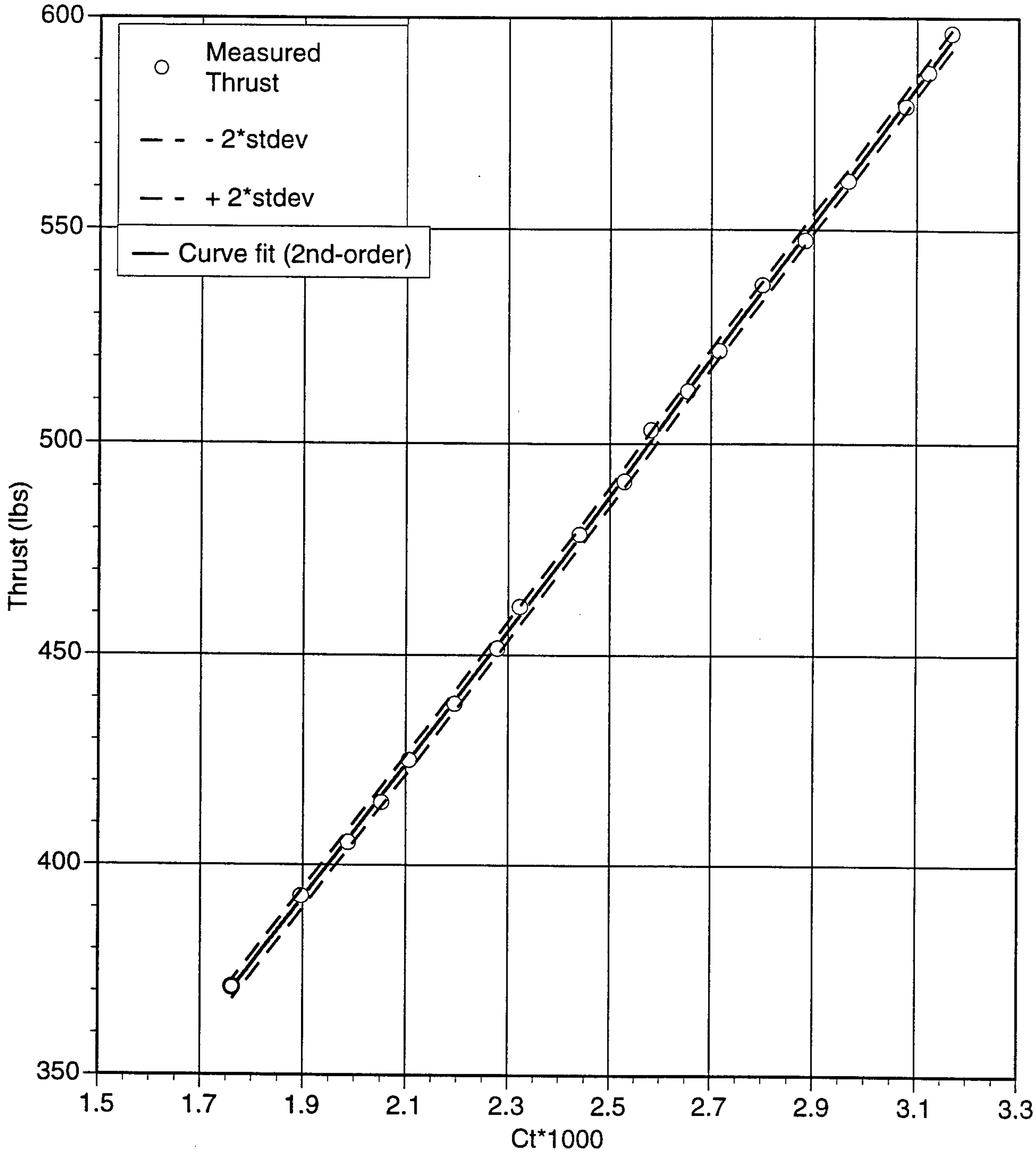

Fig. D.4. Example of model thrust measurements and uncertainty from one experiment

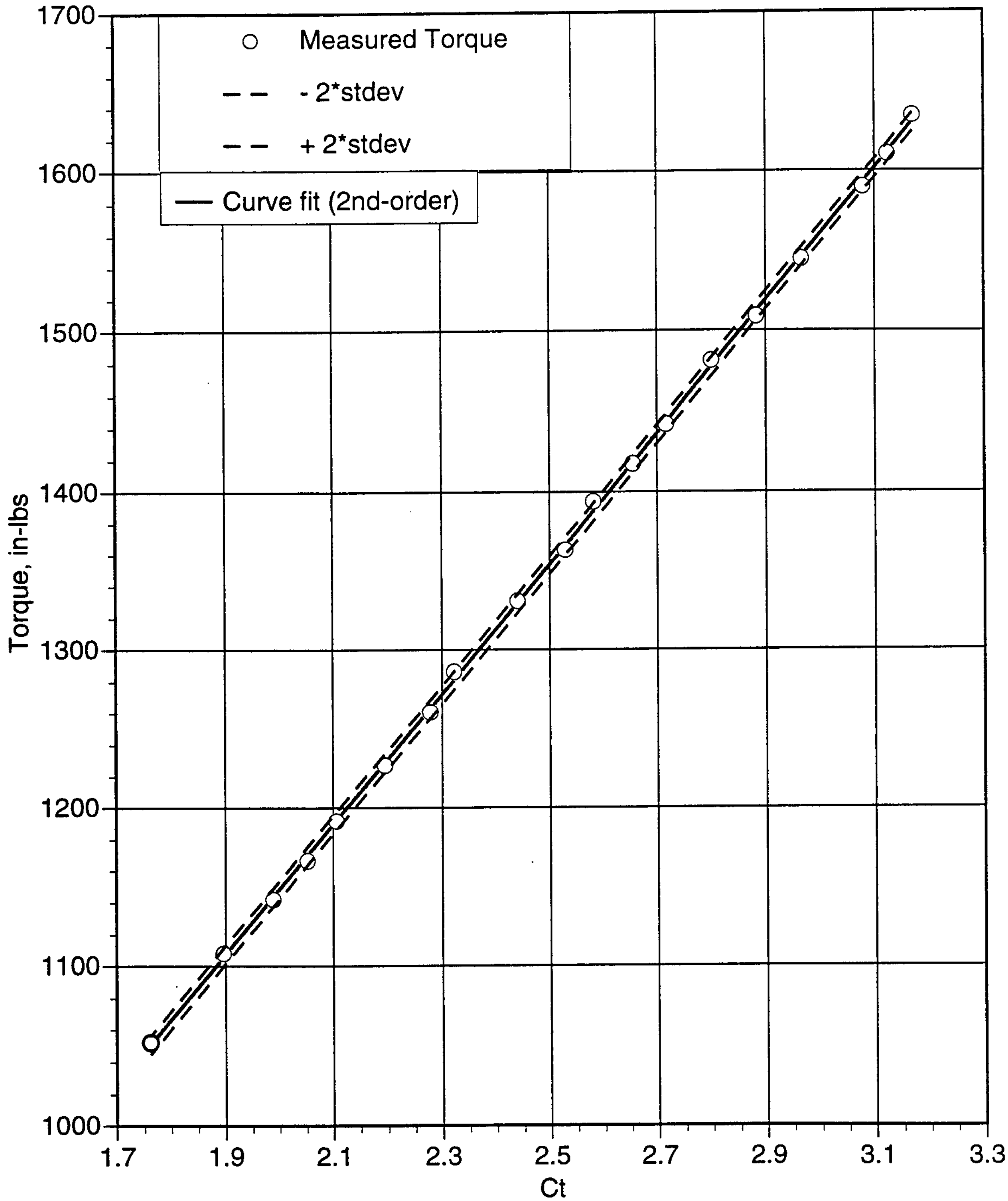

Fig. D.5. Example of model torque measurements and uncertainty from one experiment

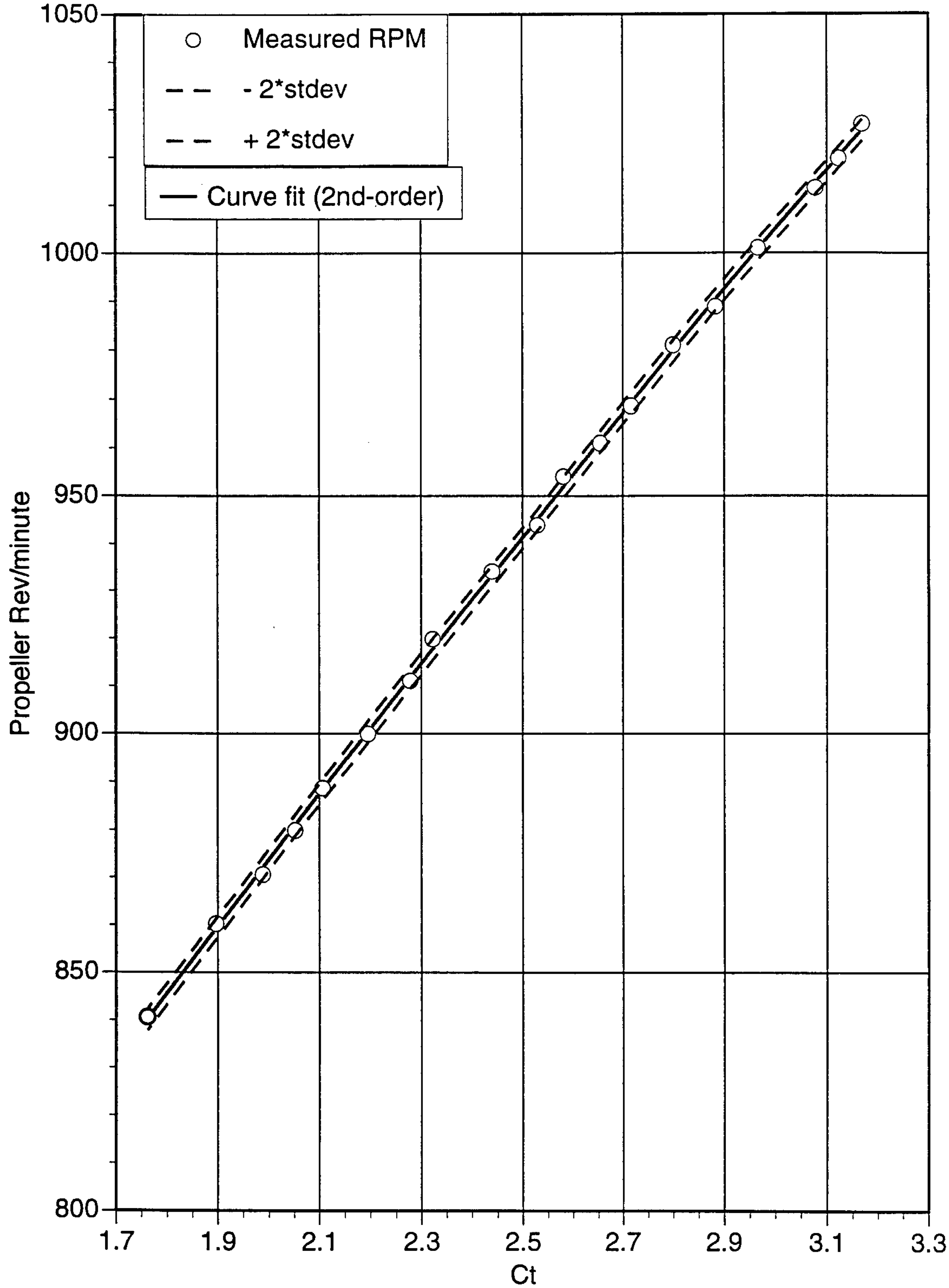

Fig. D.6. Example of model RPM measurements and uncertainty from one experiment

Table D.1. Instrumentation used for the two resistance and powering tests

INSTRUMENT		
Carriage Speed (same as model speed)	Type	magnetic pick-up to counter
	Manufacturer	Airpax
	Model	Zero-Velocity Pickup
	Wheel	520-tooth
	Counter	Hewlett Packard
	Counter Model	5316B
RPM	Type	magnetic pick-up to counter
	Manufacturer	Airpax
	Model	Zero-Velocity Pickup
	Wheel	60-tooth
	Counter	Hewlett Packard
	Counter Model	5316B
Drag Dynamometer	Manufacturer	NSWCCD
	Model	high speed 500 lb
	Type	full bridge strain gauge type
	Max drag force	500 lb
	Max lift force	500 lb
	Max side force	500 lb
	Max pitching moment	3200 ft-lbs
	Max yawing moment	3200 ft-lbs
Thrust and Torque Dynamometer	Manufacturer	Kempf & Remmers
	Model	R 58
	Type	full bridge strain gauge type
	Rated thrust	+/- 1000 lb
	Rated torque	+/- 150 lb-ft
	Max rpm in water	3600 rpm
	Overload T&Q allowed	30%
Signal Conditioner (used with drag, thrust, and torque gage)	Manufacturer	Vishay
	Model	2310
Differential DC Amplifier (used with drag, thrust, torque, rpm and speed)	Manufacturer	Ectron
	Model	751ELN

Table D.2. Calibration uncertainty for the model drag, shaft thrust, and shaft torque gages for the first resistance and powering test series.

Drag (ahead)

	Cal #1	Cal #2	Cal #3	Cal #4	Averages	2*Stdev(%) of Average Cal Factors
Range	0-400 lb, by 25 lb increment		0-100 lb, by 10 lb increment			
# of spots	31	31	19	19		
Average Cal Factor (lb/volt)	-49.4803	-49.4373	-49.4605	-49.4612	-49.4598	**0.06%**
2*Stdev (%)	0.27%	0.22%	0.11%	0.14%	**0.18%**	

Thrust (ahead)

	Cal #1	Cal #2	Averages	2*Stdev(%) of Average Cal Factors
Range	0-900 lb, by 100 lb increment			
# of spots	17	17		
Average Cal Factor (lb/volt)	99.9056	99.9016	99.9036	n/a
2*Stdev (%)	0.15%	0.15%	**0.15%**	

Torque (R.H.)

	Cal #1	Cal #2	Averages	2*Stdev(%) of Average Cal Factors
Range	0-1968.5 inlb, by 196.85 inlb increment			
# of spots	19	19		
Average Cal Factor (inlb/volt)	-241.7077	-241.8252	-241.7664	n/a
2*Stdev (%)	0.20%	0.11%	**0.16%**	

Note: The weights used for these calibrations are calibrated every 2 years to a tolerance of 0.01%

Table D.3. Calibration uncertainty for the model drag, shaft thrust, and shaft torque gages for the second resistance and powering test series.

Drag (ahead)

	Cal #1	Cal #2	Cal #3	Cal #4	Cal #5	Averages	2*Stdev(%) of Average Cal Factors
Range	0-400 lb, by 25 lb increment						
# of spots	31	31	31	31	31		
Average Cal Factor (lb/volt)	-49.8348	-49.8634	-49.8758	-49.7917	-49.8184	-49.8368	**0.12%**
2*Stdev (%)	0.42%	0.24%	0.18%	0.38%	0.24%	**0.29%**	

Thrust (ahead)

	Cal #1	Cal #2	Cal #3	Cal #4	Cal #5	Cal #6	Cal #7	Cal #8	Averages	2*Stdev(%) of Average Cal Factors
Range	0-900 lb, by 100 lb increment									
# of spots	17	17	17	17	17	17	17			
Average Cal Factor (lb/volt)	99.9320	99.9149	99.9521	99.8418	99.9064	99.8336	99.7077	99.7828	99.8589	**0.16%**
2*Stdev (%)	0.09%	0.11%	0.09%	0.24%	0.16%	0.27%	0.20%	0.10%	**0.16%**	

Torque (R.H.)

	Cal #1	Cal #2	Cal #3	Cal #4	Cal #5	Cal #6	Averages	2*Stdev(%) of Average Cal Factors
Range	0-1968.5 inlb, by 196.85 inlb increment							
# of spots	19	19	19	19	19	19		
Average Cal Factor (inlb/volt)	-226.3549	-226.4562	-226.4713	-226.4684	-226.8203	-226.7572	-226.5547	**0.15%**
2*Stdev (%)	0.07%	0.06%	0.05%	0.07%	0.04%	0.06%	**0.06%**	

Note: The weights used for these calibrations are calibrated every 2 years to a tolerance of 0.01%

Table D.4. Model speed measurement uncertainty, model test speed range of 3.5-18 knots, for the first resistance and powering test series.

3.5 knot data	
exp#	287
# of spots	36
avg	5.919
2*Stdev	0.008
%	**0.14%**

6 knot data	
exp#	288
# of spots	26
avg	10.134
2*Stdev	0.012
%	**0.12%**

10 knot data							total all
exp#	257	277	286	298	328		10 kn test
# of spots	24	28	33	21	20	# tests	5
avg	16.891	16.881	16.871	16.878	16.888	avg	16.882
2*Stdev	0.007	0.030	0.012	0.010	0.010	2*Stdev	0.014
%	0.04%	0.18%	0.07%	0.06%	0.06%	avg %	**0.08%**

16 knot data	
exp#	289
# of spots	24
avg	27.005
2*Stdev	0.042
%	**0.15%**

18 knot data												total all
exp#	263	268	272	273	278	290	294	295	305	306		18 kn test
# of spots	20	26	26	23	12	19	22	26	22	23	# tests	10
avg	30.379	30.393	30.398	30.398	30.395	30.377	30.327	30.364	30.376	30.400	avg	30.381
2*Stdev	0.013	0.040	0.024	0.037	0.021	0.020	0.020	0.057	0.031	0.027	2*Stdev	0.029
%	0.04%	0.13%	0.08%	0.12%	0.07%	0.07%	0.07%	0.19%	0.10%	0.09%	avg %	**0.10%**

Table D.5. Model speed measurement uncertainty, model test speed range of 6-18 knots, for the second resistance and powering test series.

6 knot data								total all
exp#	435	442	450	453	456	459		6 kn test
# of spots	25	23	30	30	30	31	# tests	6
avg	10.165	10.153	10.168	10.161	10.176	10.159	avg	10.164
2*Stdev	0.008	0.024	0.019	0.007	0.025	0.005	2*Stdev	0.015
%	0.07%	0.24%	0.19%	0.07%	0.24%	0.05%	avg %	**0.14%**

10 knot data				total all
exp#	436	441		10 kn test
# of spots	42	32	# tests	2
avg	16.902	16.908	avg	16.905
2*Stdev	0.010	0.030	2*Stdev	0.020
%	0.06%	0.18%	avg %	**0.12%**

16 knot data				total all
exp#	439	440		16 kn test
# of spots	24	24	# tests	2
avg	27.044	27.038	avg	27.041
2*Stdev	0.033	0.047	2*Stdev	0.040
%	**0.12%**	0.17%	avg %	**0.15%**

18 knot data														total all
exp#	432	433	434	437	438	445	446	461	462	463	464	465		18 kn test
# of spots	28	26	19	14	14	18	20	19	19	21	20	16	# tests	12
avg	30.408	30.404	30.421	30.399	30.426	30.422	30.392	30.416	30.388	30.395	30.391	30.404	avg	30.406
2*Stdev	0.019	0.029	0.021	0.023	0.109	0.060	0.024	0.017	0.055	0.040	0.025	0.027	2*Stdev	0.037
%	0.06%	0.09%	0.07%	0.07%	0.36%	0.20%	0.08%	0.06%	0.18%	0.13%	0.08%	0.09%	avg %	**0.12%**

Table D.6. Model drag measurement uncertainty, model test speed = 6,10,16,18 knots, for the first resistance and powering test series.

6 knots
10.1268 ft/sec

	RT (lbs)** (data spot)	corrected RT (6kn)
# of spots	43	43
average	47.482	47.349
2*Stdev	0.595	0.544
%	1.25	**1.15**

10 knots
16.878 ft/sec

	RT (lbs)** (data spot)	corr RT (10 kn)
# of spots	112	112
average	133.487	133.423
2*Stdev	1.580	1.554
%	1.18	**1.16**

16 knots
27.005 ft/sec

	RT (lbs)** (data spot)	corr RT (16 kn)
# of spots	25	25
average	320.207	320.837
2*Stdev	3.768	3.121
%	1.18	**0.97**

18 knots
30.3804 ft/sec

	RT (lbs)** (data spot)	corr RT (18 kn)
# of spots	26	26
average	395.952	396.221
2*Stdev	4.410	4.515
%	1.11	**1.14**

Total Average % **1.11**

** each data spot = an average of 2000 samples collected over a 5 second collection time at a rate of 400 samples/sec.

Table D.7. Model drag measurement uncertainty, model test speed = 6,10,16,18 knots, for the second resistance and powering test series.

6 knots
10.1268 ft/sec

	RT (lbs)** (data spot)	corrected RT (6kn)
# of spots	171	171
average	47.688	47.359
2*Stdev	0.551	0.521
%	1.16	**1.10**

10 knots
16.878 ft/sec

	RT (lbs)** (data spot)	corrected RT (10kn)
# of spots	38	38
average	131.986	131.712
2*Stdev	1.300	1.148
%	0.98	**0.87**

16 knots
27.005 ft/sec

	RT (lbs)** (data spot)	corrected RT (16kn)
# of spots	14	14
average	313.106	312.790
2*Stdev	0.989	0.922
%	0.32	**0.29**

18 knots
30.3804 ft/sec

	RT (lbs)** (data spot)	corrected RT (18kn)
# of spots	62	62
average	383.816	383.846
2*Stdev	1.771	2.094
%	0.5	**0.5**

Total Average % **0.70**

** each data spot = an average of 2000 samples collected over a 5 second collection time at a rate of 400 samples/sec.

Table D.8. Model thrust, torque, and rpm measurement uncertainty, model test speed=18 knots, for the first resistance and powering test series.

Thrust

18 knot data										
exp#	263	268	272	273	278	290	294	295	305	306
# of spots	20	26	26	23	12	19	22	26	22	23
2*Stdev (%)	0.758	0.761	0.293	0.467	0.416	0.364	0.449	0.919	0.274	0.285

Thrust

	total all 18 kn test
# tests	10
2*Stdev	**0.50** %

Torque

18 knot data										
exp#	263	268	272	273	278	290	294	295	305	306
# of spots	20	26	26	23	12	19	22	26	22	23
2*Stdev (%)	0.700	0.647	0.297	0.456	0.703	0.371	0.402	0.794	0.257	0.295

Torque

	total all 18 kn test
# tests	10
2*Stdev	**0.49** %

RPM

18 knot data										
exp#	263	268	272	273	278	290	294	295	305	306
# of spots	20	26	26	23	12	19	22	26	22	23
2*Stdev (%)	0.335	0.321	0.156	0.237	0.534	0.164	0.214	0.436	0.134	0.150

RPM

	total all 18 kn test
# tests	10
2*Stdev	**0.27** %

Table D.9. Model thrust, torque, and rpm measurement variation, model test speed=18 knots, for the second resistance and powering test series.

Thrust

18 knot data												
exp#	432	433	434	437	438	445	446	461	462	463	464	465
# of spots	28	26	19	14	14	18	20	19	19	21	20	16
2*Stdev (%)	1.067	0.758	1.232	0.358	1.091	0.466	0.561	0.354	0.478	0.520	0.404	0.368

Thrust

	average of all 18 kn test
# tests	12
2*Stdev	**0.64** %

Torque

18 knot data												
exp#	432	433	434	437	438	445	446	461	462	463	464	465
# of spots	28	26	19	14	14	18	20	19	19	21	20	16
2*Stdev (%)	0.504	0.519	0.258	0.352	1.072	0.442	0.525	0.347	0.422	0.507	0.441	0.337

Torque

	average of all 18 kn test
# tests	12
2*Stdev	**0.48** %

RPM

18 knot data												
exp#	432	433	434	437	438	445	446	461	462	463	464	465
# of spots	28	26	19	14	14	18	20	19	19	21	20	16
2*Stdev (%)	0.225	0.236	0.110	0.164	0.517	0.226	0.252	0.164	0.237	0.235	0.230	0.168

RPM

	average of all 18 kn test
# tests	12
2*Stdev	**0.23** %

APPENDIX E:
UNCERTAINTIES OF FULL-SCALE MEASUREMENTS

The relative total (precision + bias) uncertainties of full-scale measurements of the ship speed, propeller rpm, thrust, torque, and shaft horsepower reported for four full-scale trials (USS Boise SSN764, USS Columbus SSN762, USS Charlotte SSN 766, USS Memphis SSN 691) are given below

Reported uncertainties of full-scale measurements

ship	speed	rpm	thrust	torque	SHP
SSN 764	0.6%	1.9%	4.1%	0.3%	1.9%
SSN 762	0.6%	0.5%	4.1%	0.3%	0.6%
SSN 766	0.3%	0.2%	2.2%	0.9%	0.8%
SSN 691	n/a	0.2%	2.2%	1.4%	0.9%

Appreciable variations can be observed in the foregoing uncertainties. Reasonable estimates of these uncertainties are listed below

Uncertainties of full-scale measurements used in analysis

speed	rpm	thrust	torque	SHP
0.6%	0.4%	3.0%	0.9%	0.9%

These estimates of full-scale measurement uncertainties are used in the present analysis.

REFERENCES

[1] Hugh W. Coleman and W. Glenn Steele, *Experimentation and uncertainty analysis for engineers*, 1989, John Wiley and Sons.

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